ETH zürich

Hydropower expansion:
Dam heightening and hydraulics of bottom outlets

Frontiers in Energy Research

B. Hohermuth, Dr. L. Schmocker, Prof. Dr. R. Boes

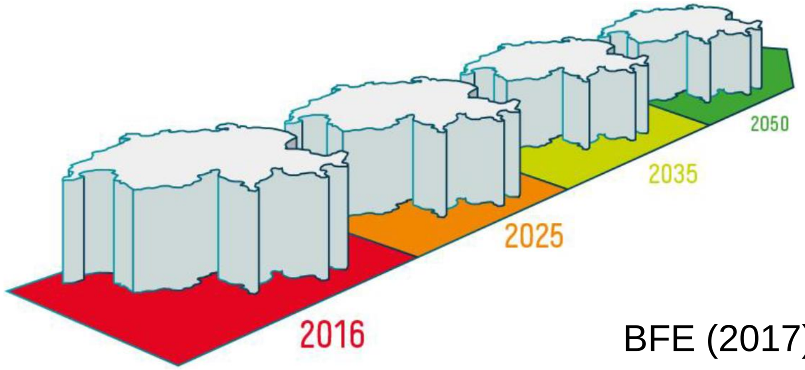
Laboratory of Hydraulics,
Hydrology and Glaciology

Outline

- Swiss energy strategy 2050
- The role of hydropower
- Hydropower plants & bottom outlets
- Hydraulic scale modeling
- Results
- Conclusions

Swiss Energy Strategy 2050

Key points



BFE (2017)

- Reduce consumption / increase energy efficiency
  - -21% reduction in electricity consumption by 2050 (compared to 2010) per capita
  - Total electricity consumption -9% (57.6 TWh/a)
- Increase the use of renewable energy
  - New renewables: 24.2 TWh/a
  - New hydropower: 6.1 TWh/a
- Withdrawal from nuclear energy
  - Step-wise withdrawal (no ban on nuclear technology)
- Energy research

BFE (2017), Prognos (2012)

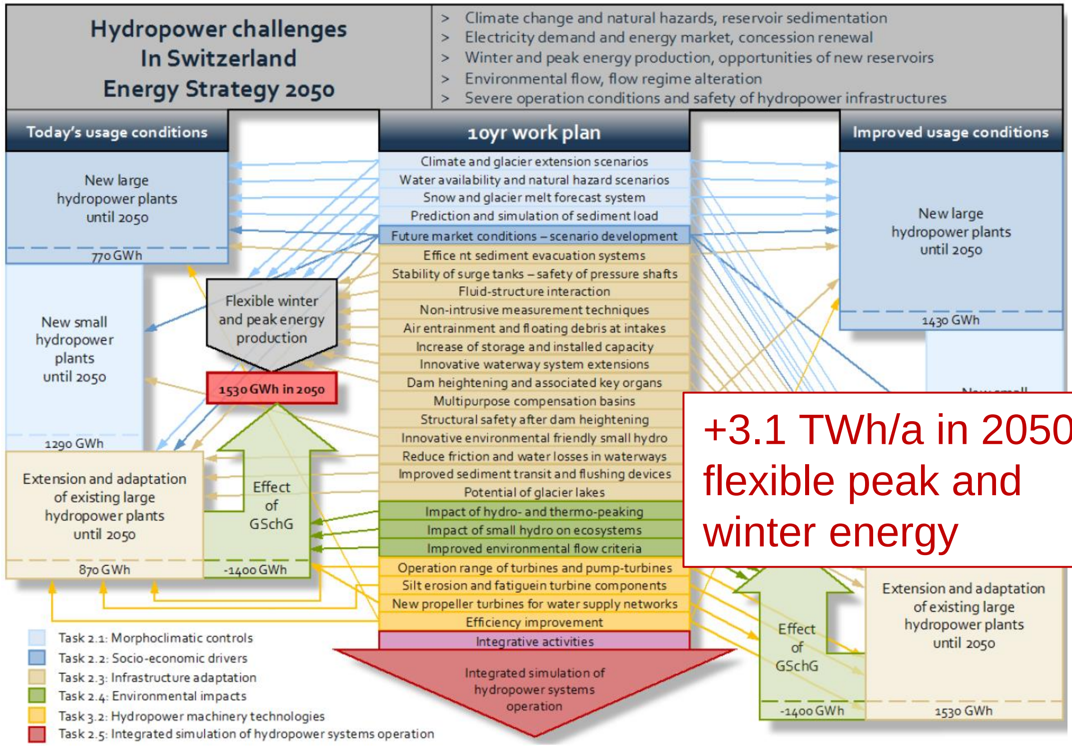
Energy research

SCCER-SoE

Swiss Competence Center for Energy Research – Supply of Electricity

Workpackage Hydropower
- Forecasting models / Climate change
- New periglacial hydropower
- Infrastructure adaptions
- Environmental impacts

Workpackage Geo-energy → 4.4 TWh/a



+3.1 TWh/a in 2050 flexible peak and winter energy

www.sccer-soe.ch

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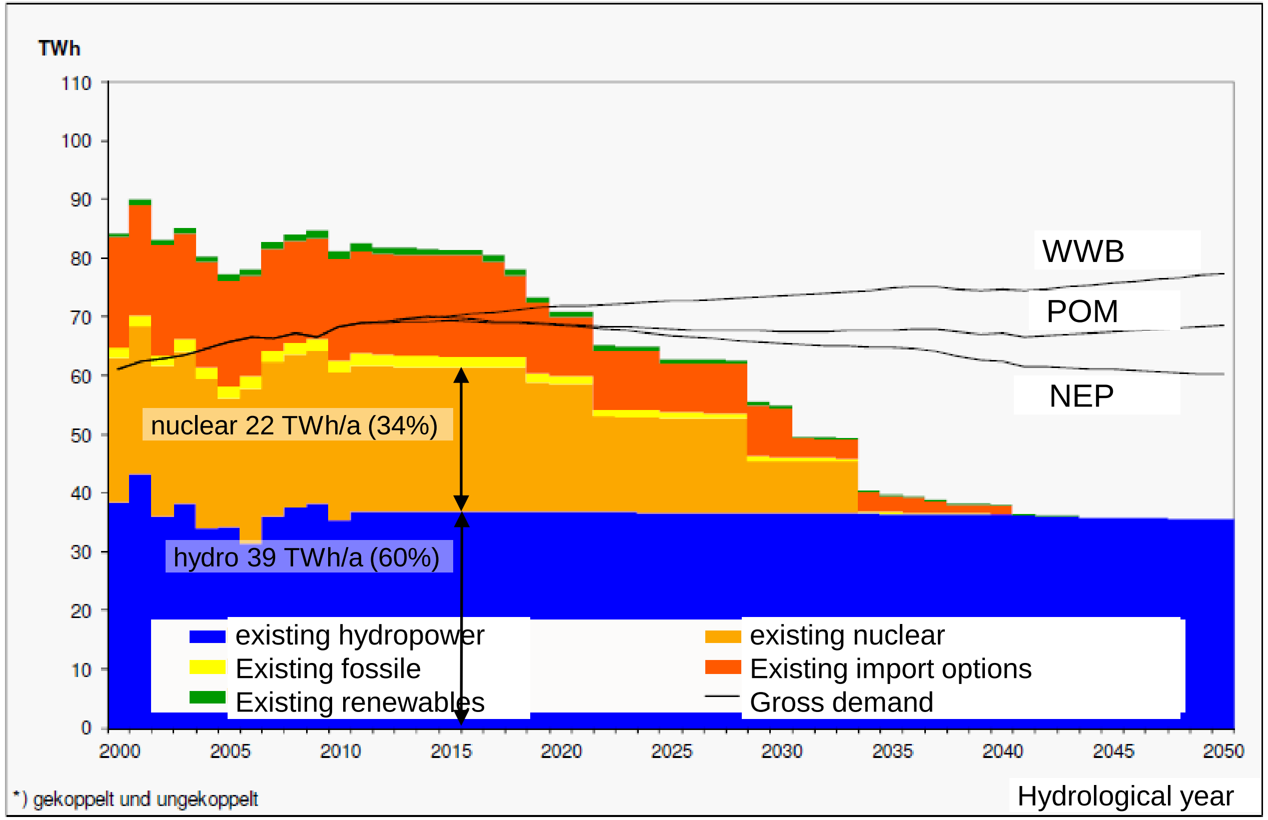
Electricity demand and supply in 2050

Prognos (2012) «Energy perspectives for Switzerland in 2050»

Scenarios:

- Business as usual (WWB)
- Political measures (POM)
- New energy policy (NEP)



Prognos (2012)

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Electricity demand and supply in 2050

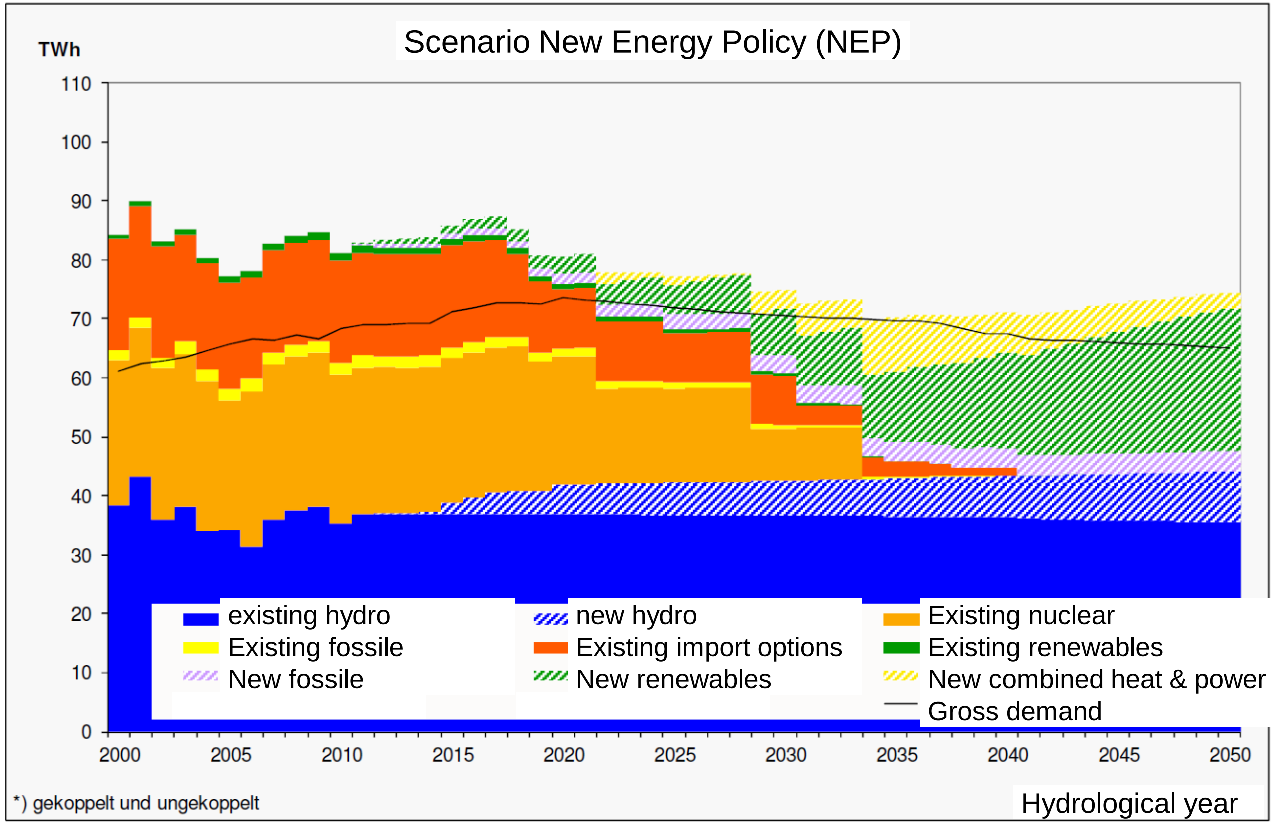
Simulated supply in 2050

Winter half year [TWh/a]	2010	2050
Gross demand	36.8	36.0
Nuclear	14.1	-
Renewables	0.8	10.5
Hydro	14.2	20.9
Conventional thermal	1.3	4.7
Imports	9.36	-
Exports	4.1	0.0

Source: Prognos (2012)

Hydro 2010-2014: 16.4 TWh/a (BFE 2015)

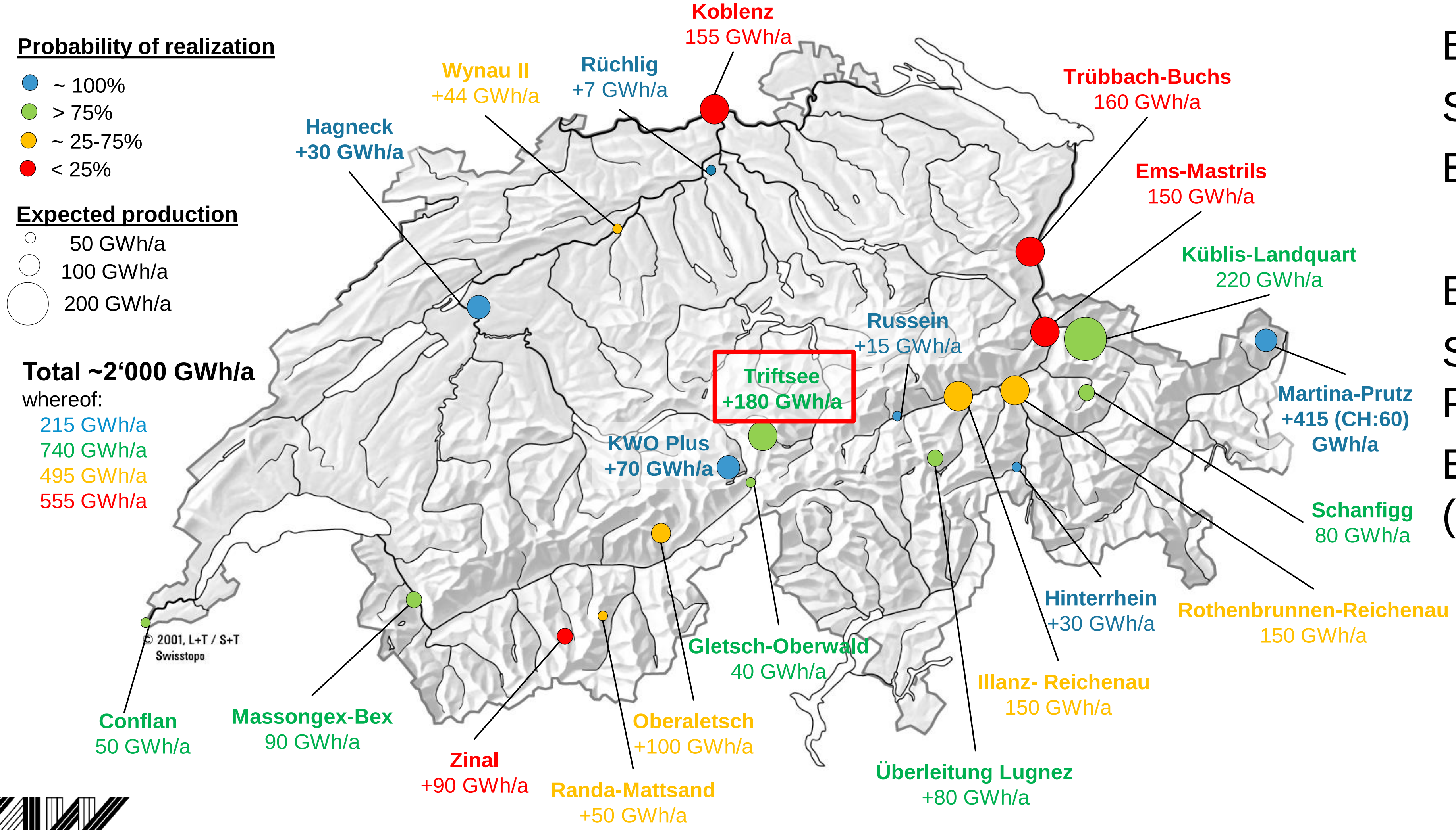
+4.5 TWh/a



Prognos (2012)

Hydropower expansion

Possible projects in near future



Estimated potential

SWV (2012): 0-5 TWh/a

BFE (2012): 3.1 TWh/a

BFE (2012):

Small hydro: 1.6 TWh/a

P < 10 MW

Env. flow: -1.4 TWh/a (GSchG)

Map: After SWV; Soures: BFE (2012), SWV (2013), VAW (2014+2016)

New hydropower

Periglacial environment

Development of the Trift glacier

www.grimselverein.ch

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New hydropower

Periglacial environment

Visualization Trift arch dam 2025???

Kraftwerke Oberhasli

Seasonal variations

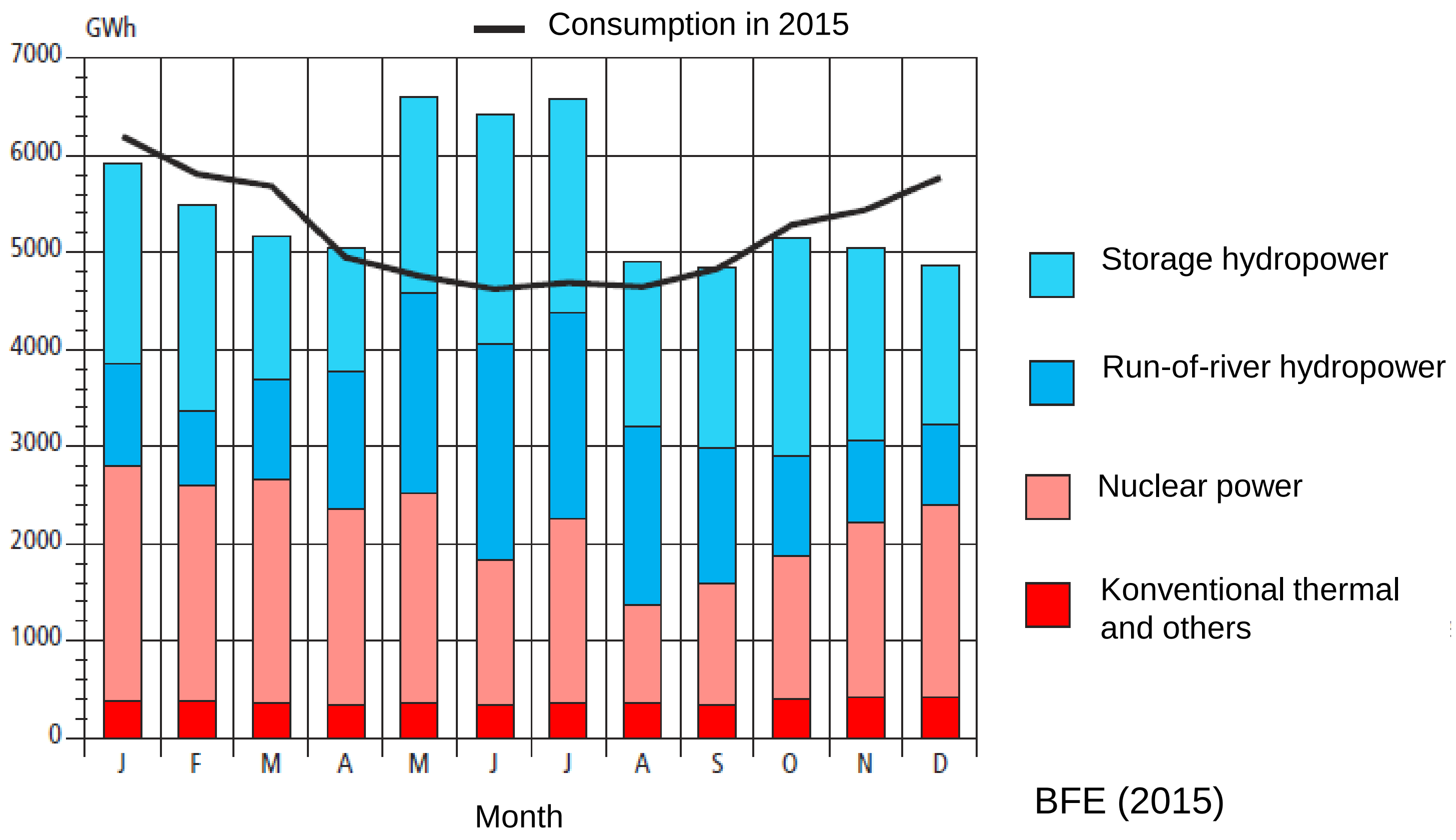
Storage hydropower

Seasonal energy balance

- Exports during summer
- Imports during winter

Expected energy gap in 2050

~ 3 TWh in winter*



BFE (2015)

*Boes (2016)

Seasonal variations

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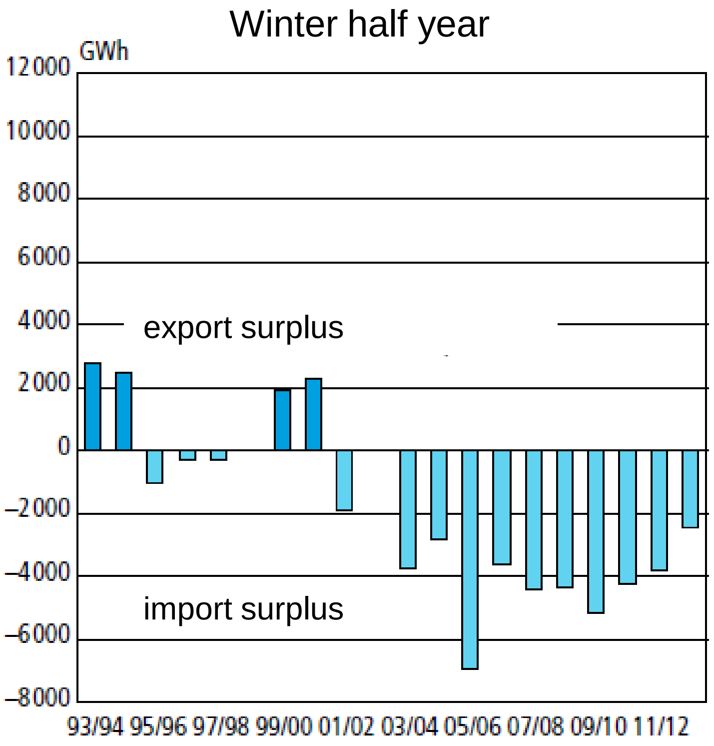

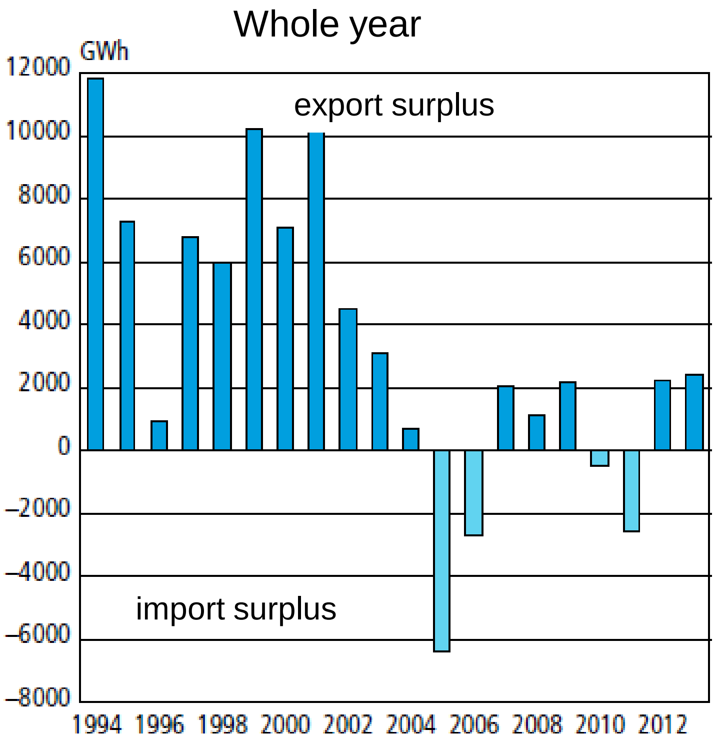

*Boes (2016)

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Seasonal variations
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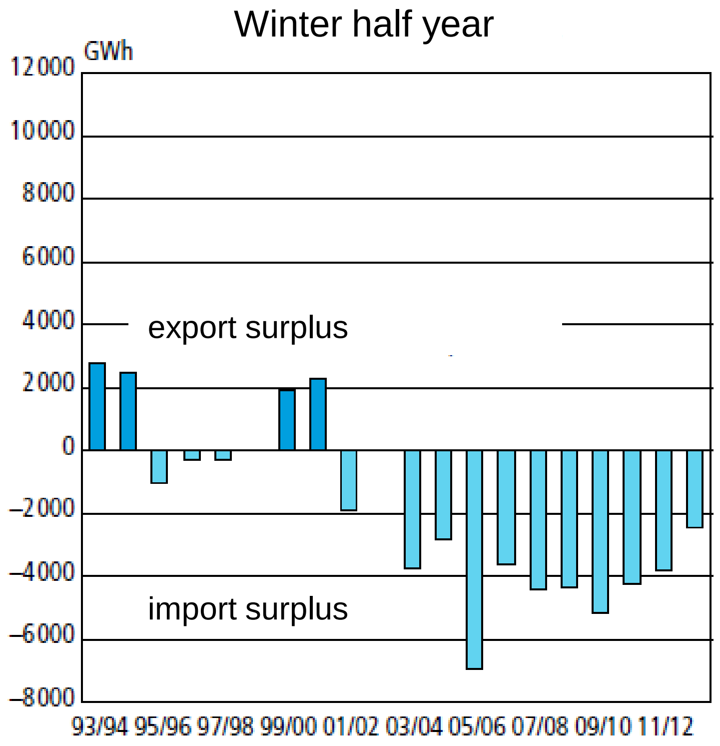
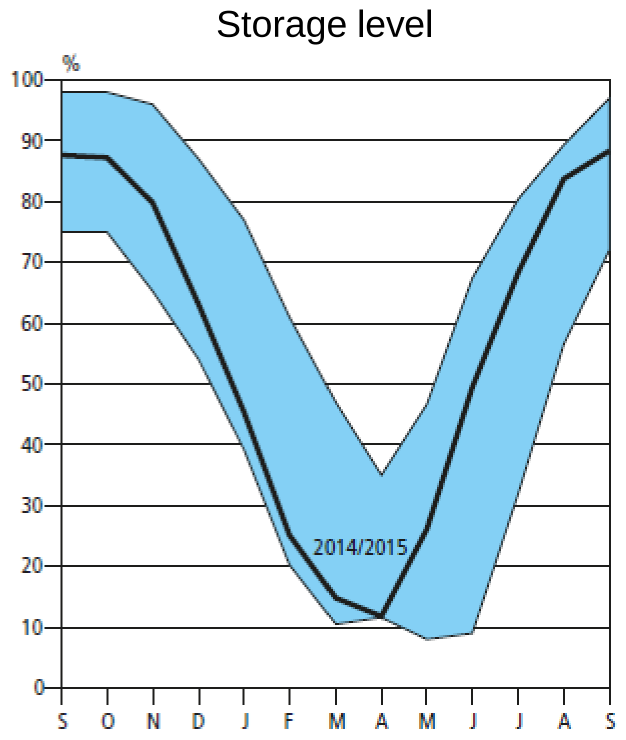


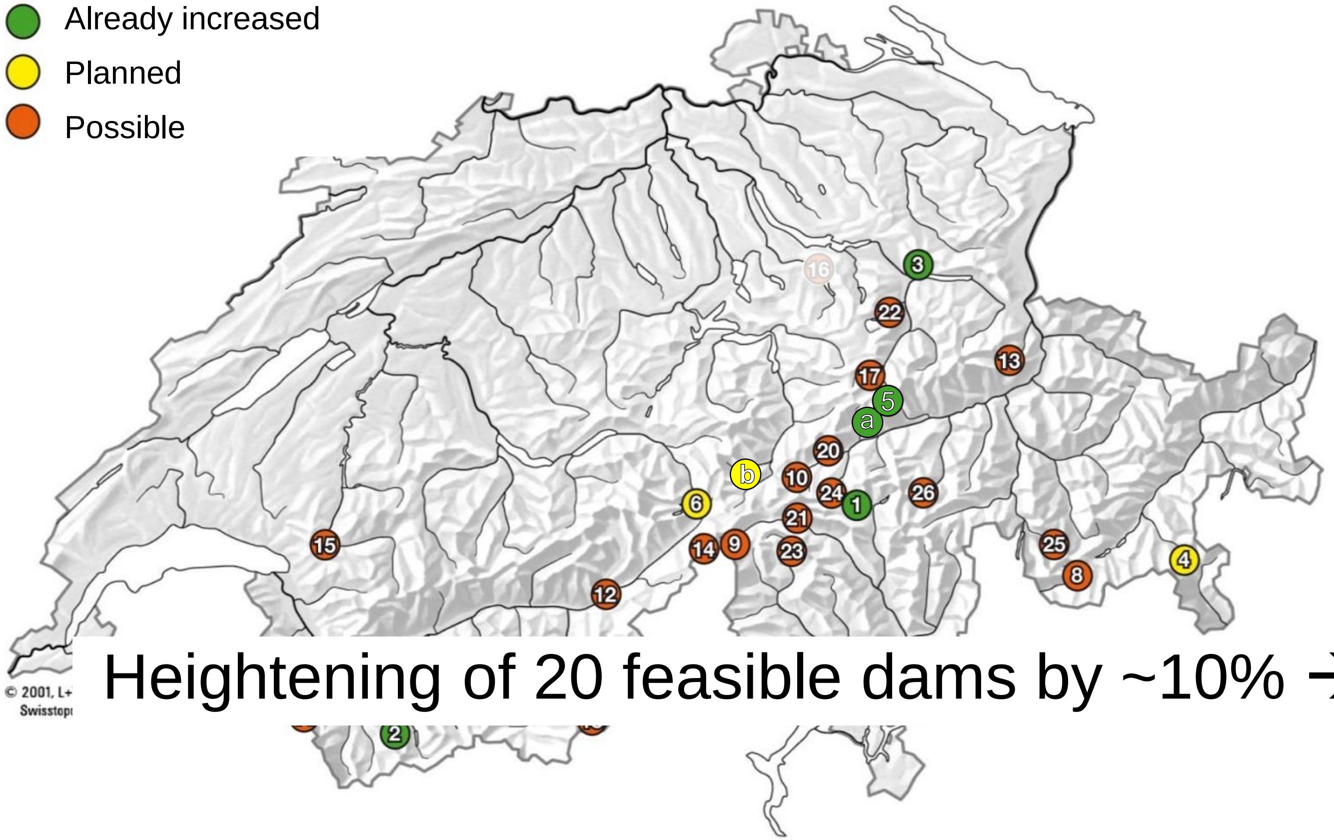


*Boes (2016)

BFE (2015)

Increase winter storage

Dam heightening



Already increased:
1 Luzzone (17 m)
2 Mauvoisin (13.5 m)
3 Muslen (5 m)
5 Muttsee (neu, 35 m)
7 Vieux-Emosson (20 m)
a Barcuns (5 m)

Planned:
4 Lago Bianco N/S
6 Spitallamm/Seeuferegg (101 hm^3)
b Göscheneralp (76 hm^3)

Possible:
8 Albigna (70 hm^3)
9 Cavagnoli (29 hm^3)
10 Curnera (40.8 hm^3)
11 Emosson (227 hm^3)
12 Gebidem (9.2 hm^3)
13 Gigerwald (33.4 hm^3)
14 Gries (18 hm^3)
15 Hongrin (52 hm^3)
~~16 In den Schlagen/ Hünermattdamm~~
17 Limmern (92 hm^3)
18 Mattmark (100 hm^3)
19 Moiry (77 hm^3)
20 Nalps (44.5 hm^3)
21 Piora (47.5 hm^3)
22 Rhodannenberg (39.8
25 Valle di Lei (197 hm^3)
26 Zervreila (100 hm^3)

Heightening of 20 feasible dams by ~10% → +25% Storage volume (2 TWh)

Map: SWV; Data: BFE (2004), EPFL (2012), VAW (2016)

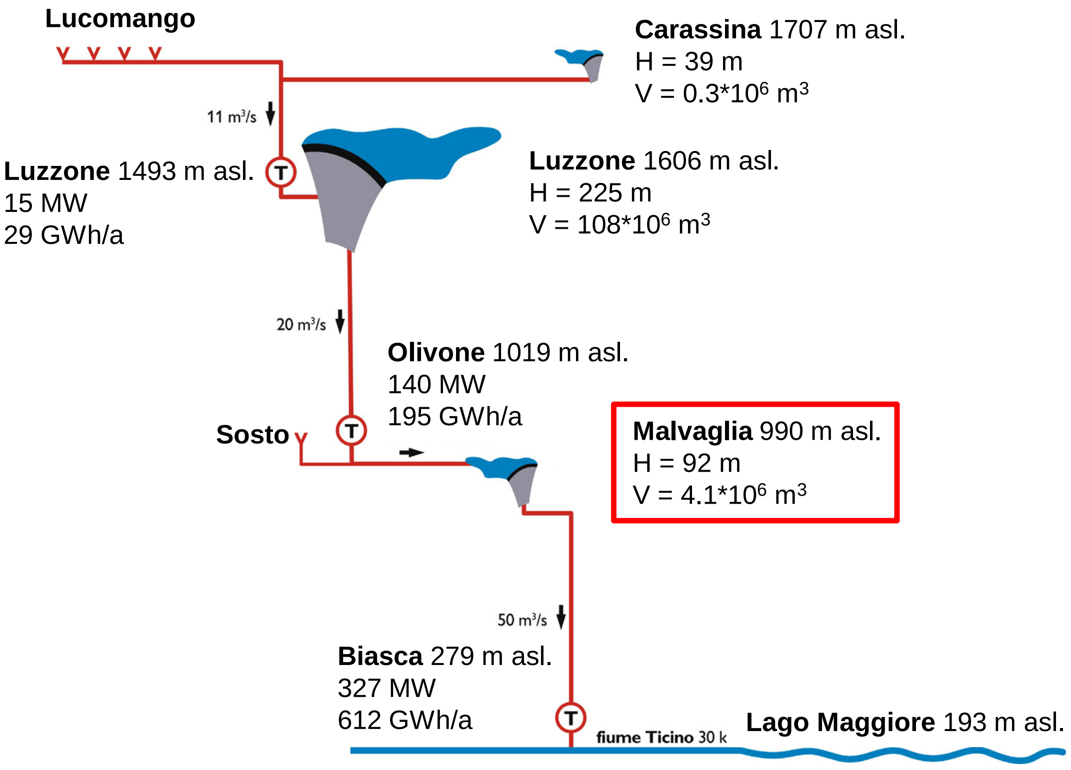
Summary: Swiss Energy Strategy 2050
The role of hydropower

- Increase in electricity production from hydropower, **estimated potential 0 – 5 TWh/a** depending on political/regulatory framework
- Flexiblity & **seasonal storage** becomes more important
- **Production loss -1.4 TWh/a** due to new environmental regulation
- **Limited production increase** from update/renewal of existing plants
- **Heightening of existing dams** leads to a **2 TWh increase in storage capacity**
- Possibly **large potential** for new hydro in the **periglacial environment**

→ Closing of the (winter) energy gap seems challenging but possible

Storage hydropower scheme

General layout: Blenio HPP



Dam heightening Luzzone (1998)

Storage hydropower scheme

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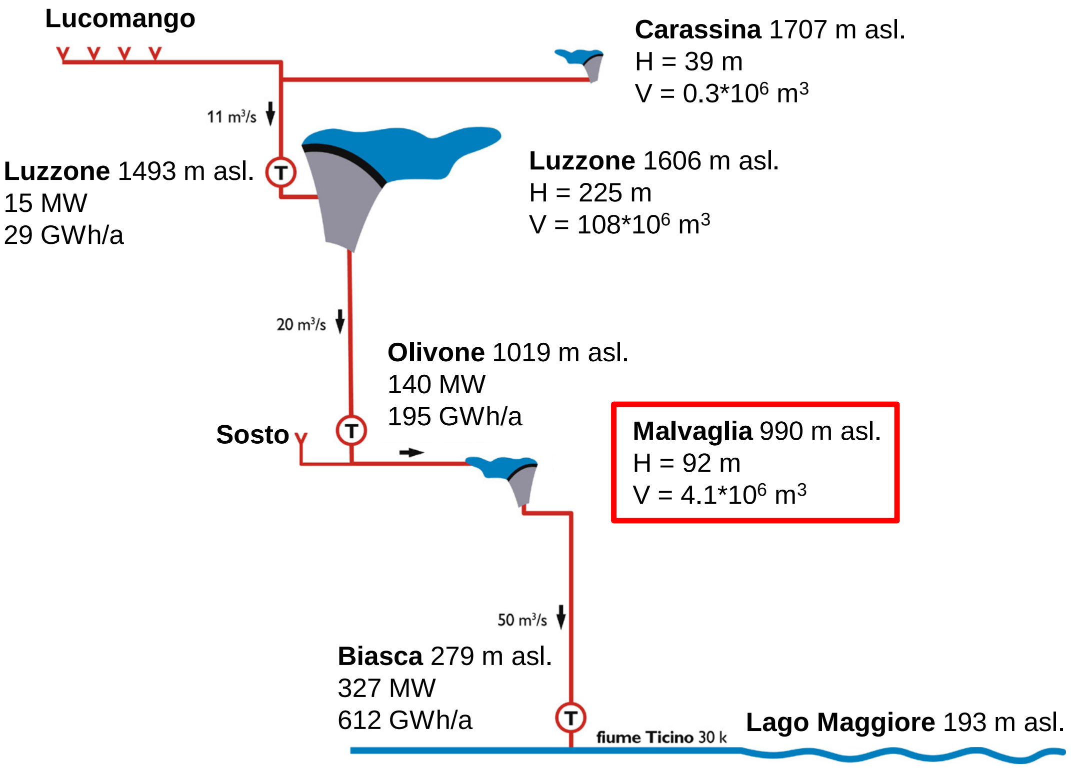

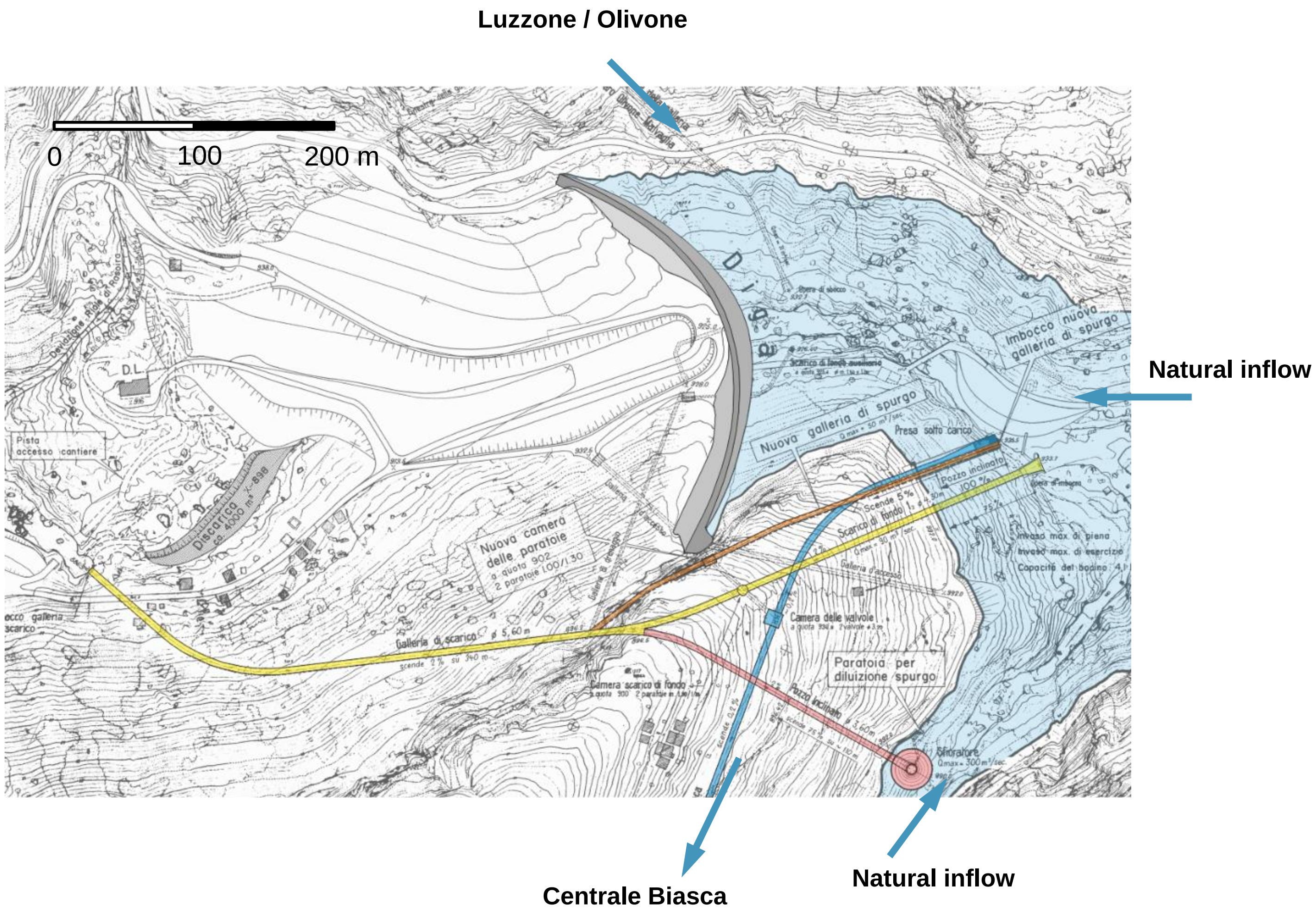

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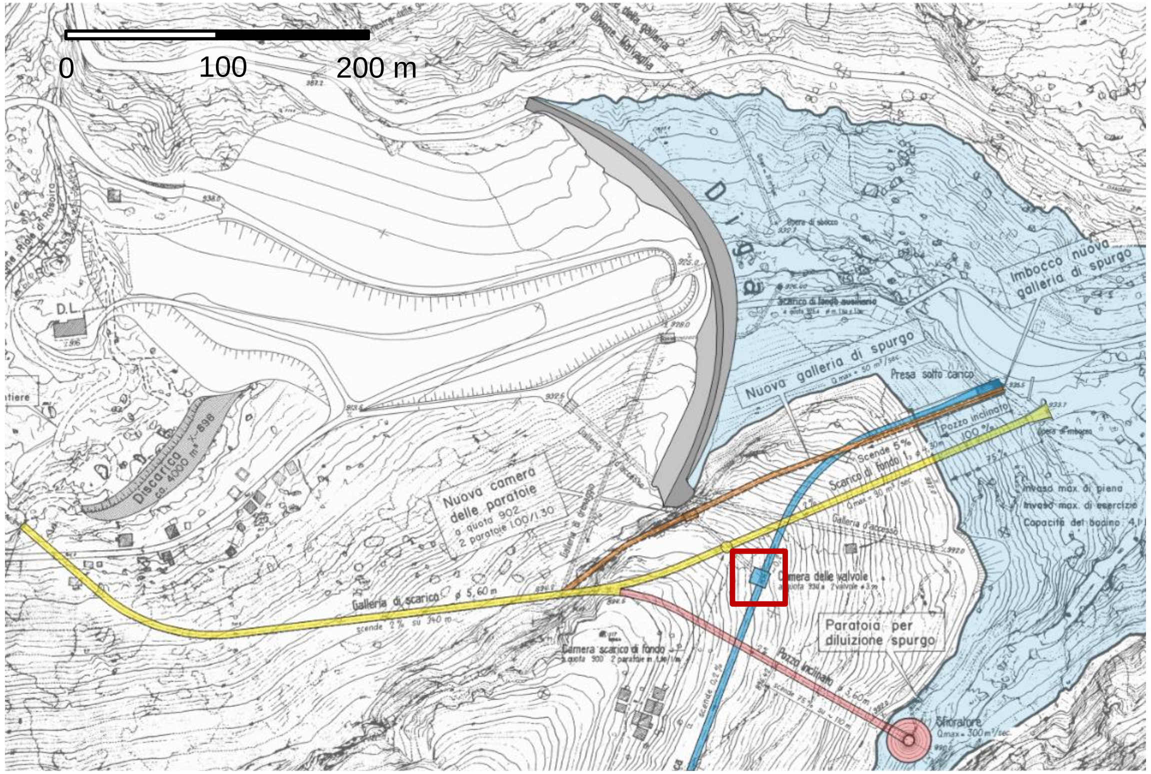
Storage hydropower scheme

Appurtenant structures

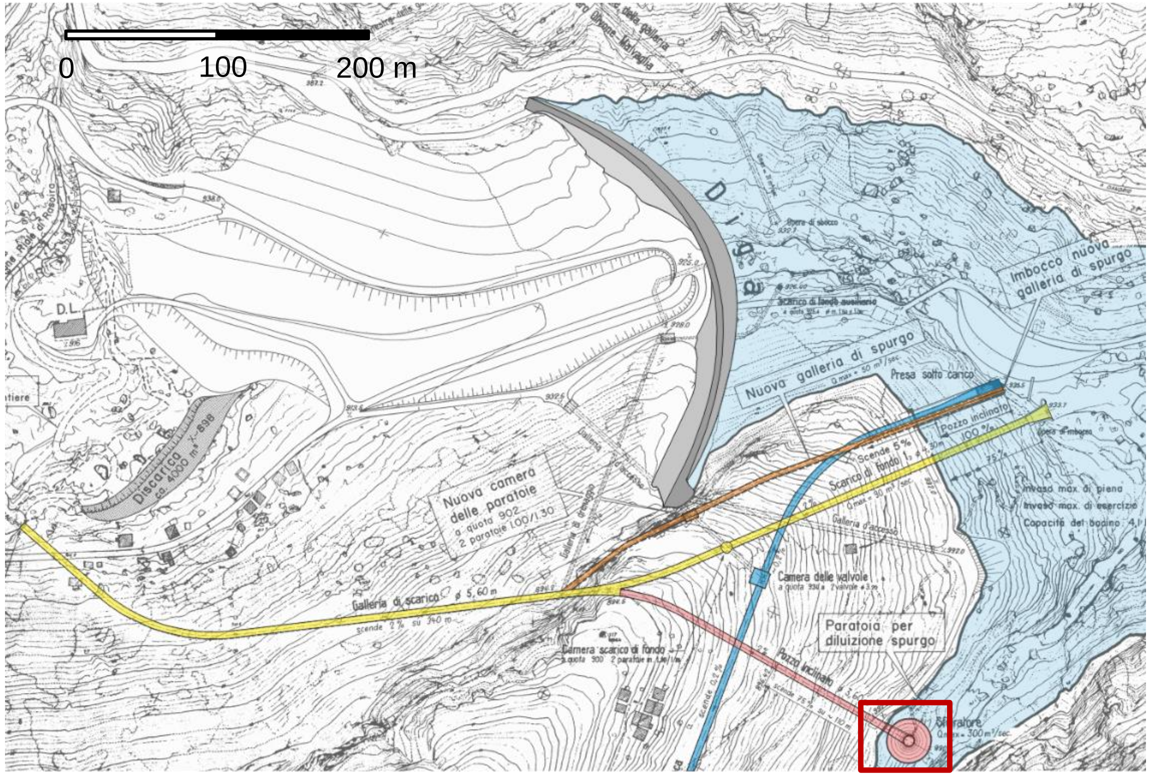
Butterfly valves (penstock)



Storage hydropower scheme

Appurtenant structures

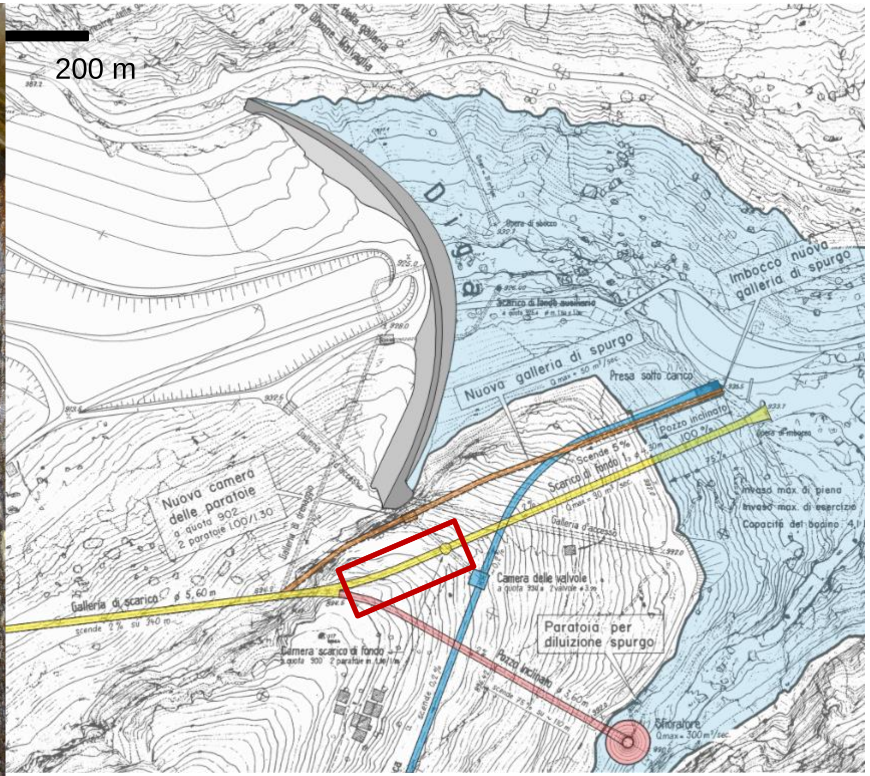
Moring glory (spillway)



Storage hydropower scheme

Appurtenant structures

Bottom outlet gate (outlet tunnel)



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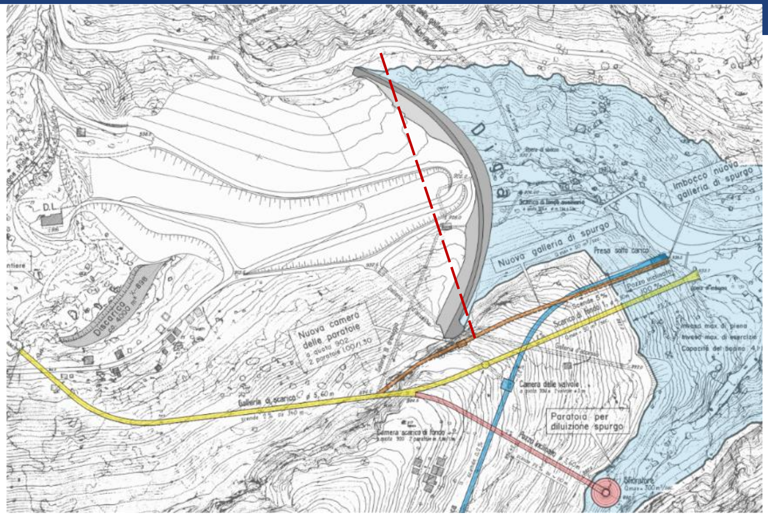
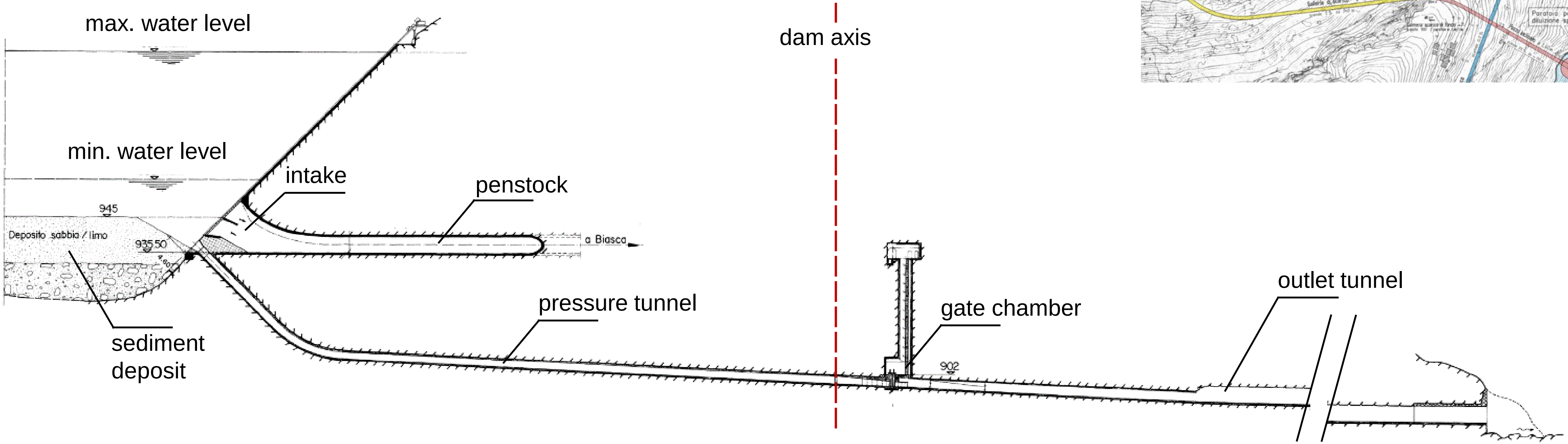
Storage hydropower scheme

Bottom outlet

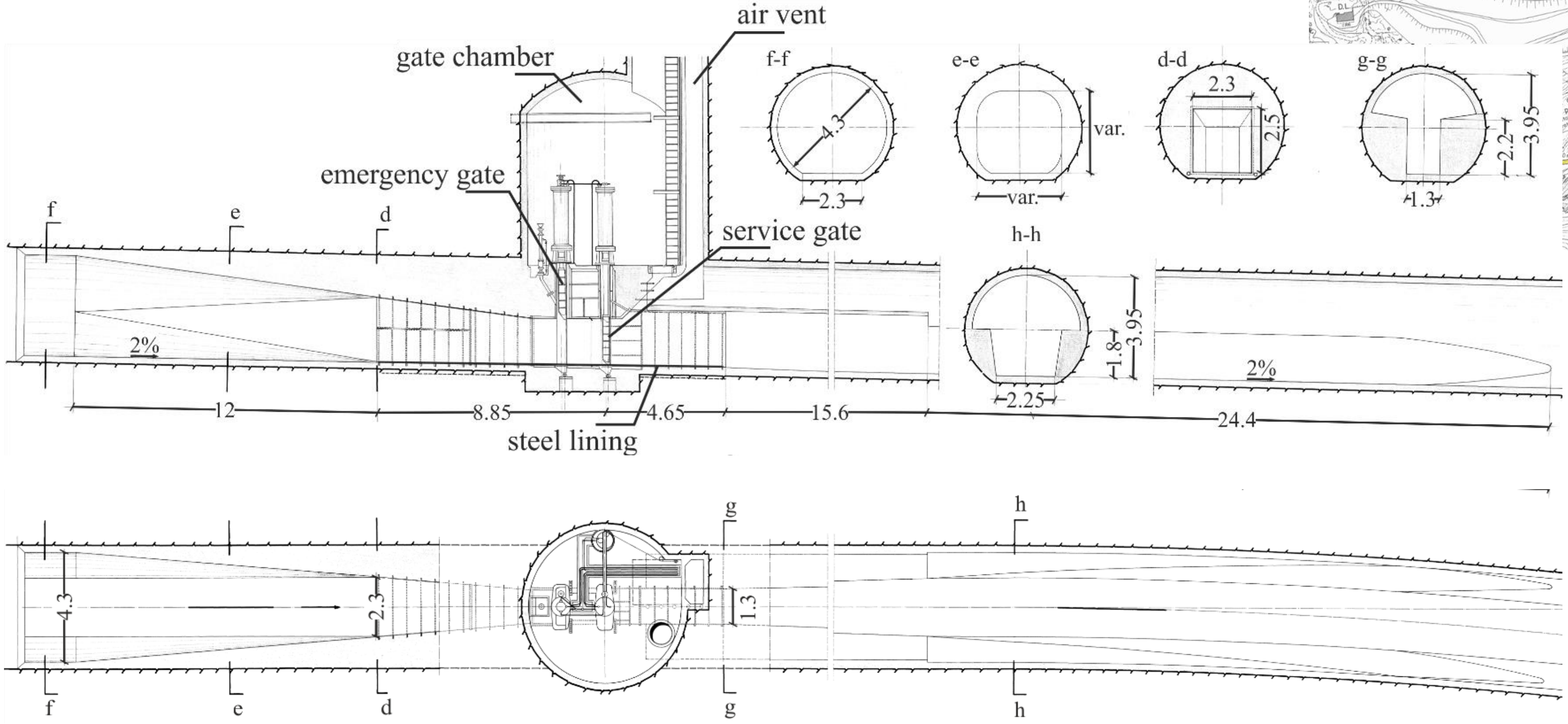


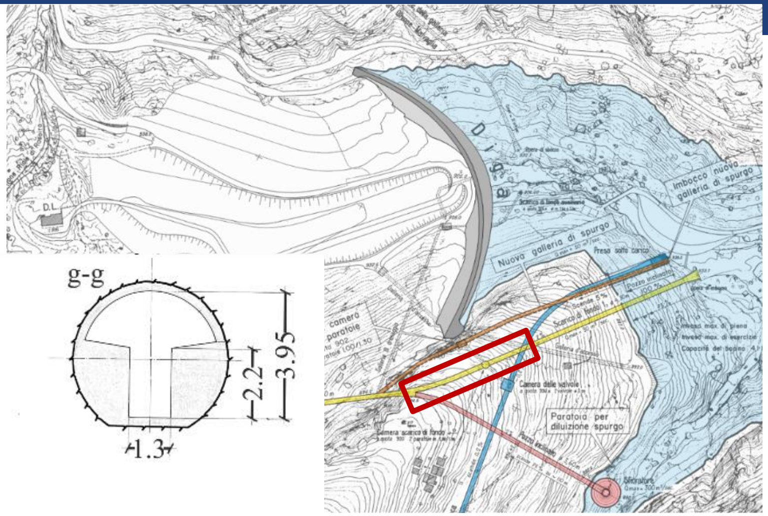


Logitudinal section new «flushing» bottom outlet

Storage hydropower scheme

Bottom outlet





Bottom outlet

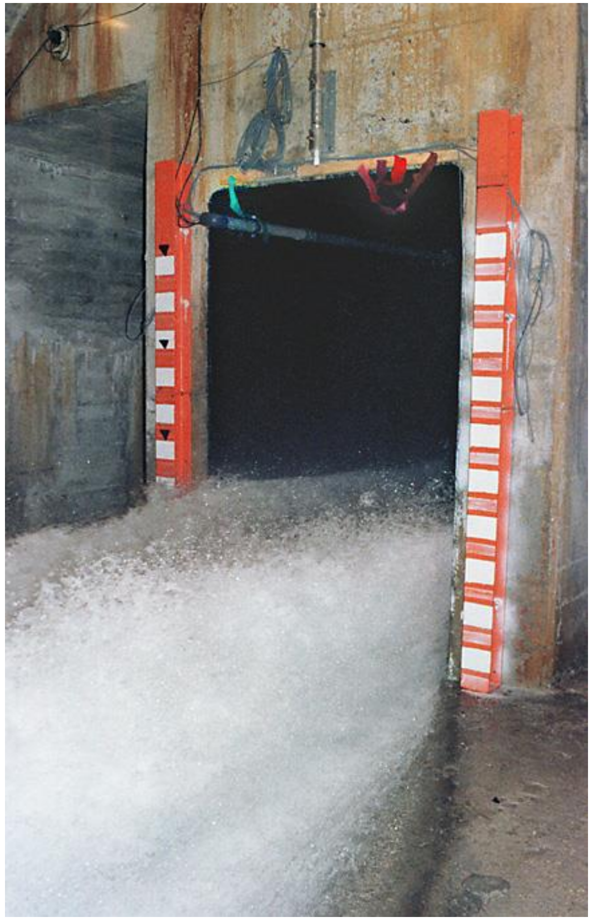
Key safety device

Purposes:

- Control of reservoir level
- Sediment flushing
- Flood discharge

Requirements:

- Sufficient capacity
- Reliable performance for all gate openings
- Long lifetime



Bottom outlet Panix (Speerli 1994)

Bottom outlets: Challenges

Cavitation

Cavitation index

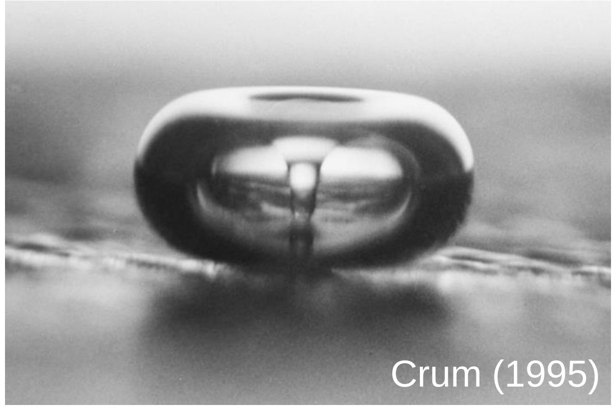
$$\sigma = \frac{p + p_{amb} - p_v}{\rho U^2}$$

- p_{amb} – ambient pressure
- p_v –water vapor pressure
- p – hydrodynamic water pressure
- U – flow velocity

No cavitation for $\sigma > 0.25$

No cavitation damage for $c_b > 0.01$

(Falvey 1990, Kramer *et al.* 2005)


Crum (1995)

Imploding cavitation bubble

Minor (2000)

Cavitation damage on smooth concrete

Bottom outlets: Challenges

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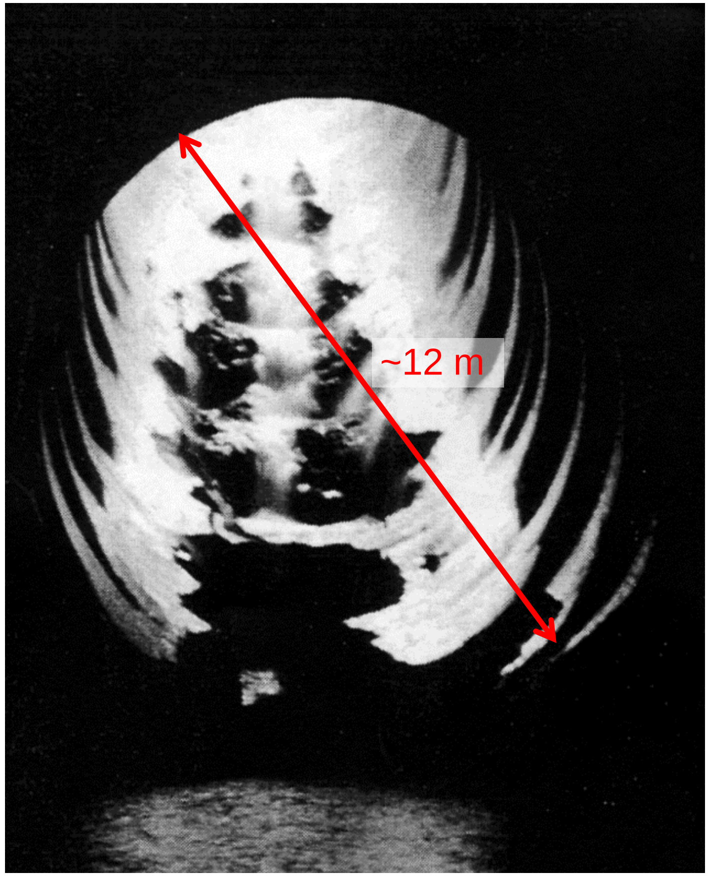


Cavitation damage “Christmas tree”
Glen Canyon Dam (Falvey 1990)

Bottom outlets: Challenges

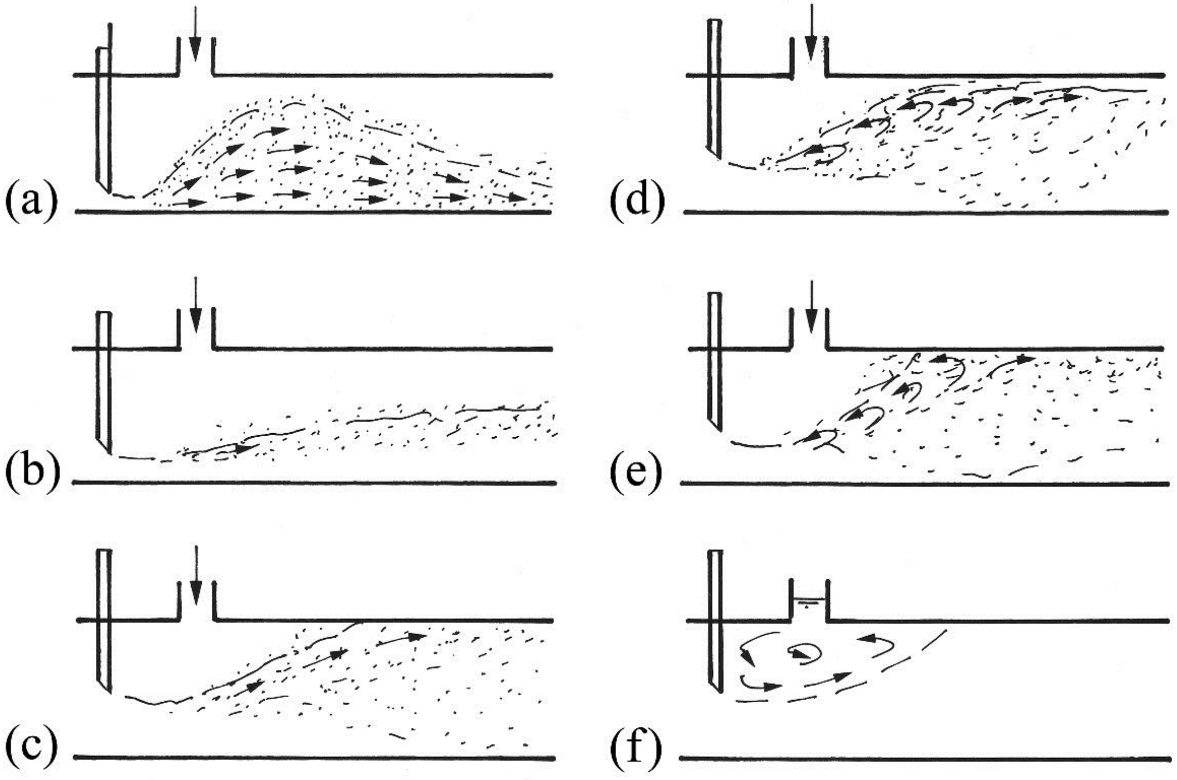
Gate vibration & Flow choking

Gate vibration

- Dampend spring-mass system
- Excited by flow detachment / negative pı

Flow choking

- Transition from free surface to pressurized flow
- Pressure shocks
- Intermittent flow patterns e.g. slug flow



Flow pattern in bottom outlets (Sharma 1973)

Bottom outlets: Challenges

Gate vibration & Flow choking

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- Excited by flow detachment / negative pressure

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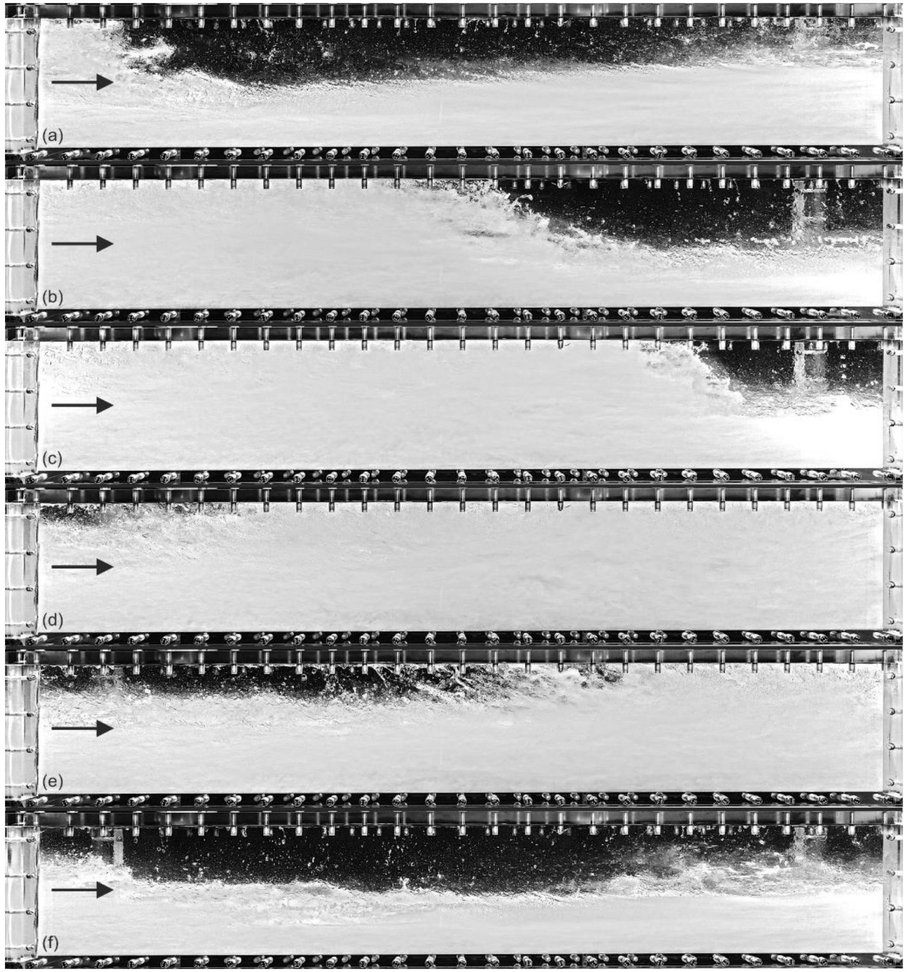

Photo sequence of slug flow in bottom outlet model

Bottom outlets: Challenges

Infrastructure adaptions

Most bottom outlets were designed and built decades ago

Increasing demands in the near future

- Dam heightening
- Higher flood peak discharges
- Inceased reservoir sedimentation

} Climate change

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Bottom outlet design

State of the art

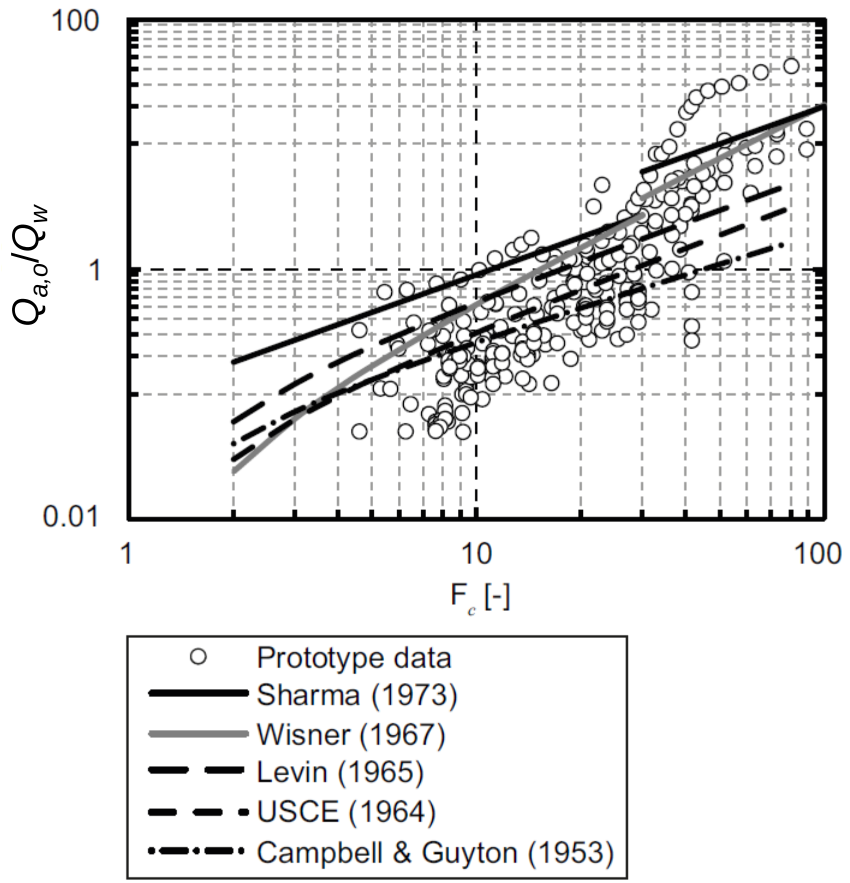
Avoidance of:

- Cavitation: $\sigma > 0.25$, $c_b > 0.01$
- Gate vibration: $p_a > -1.5$ m w.c.
- Flow transition / choking: ???

Information on:

- Air demand & air pressure
- Two-phase flow hydraulics e.g. air concentration
- Flow transition mechanism

Comparison of air demand formulas



PhD Project: “Aeration & two phase flow in bottom outlets”

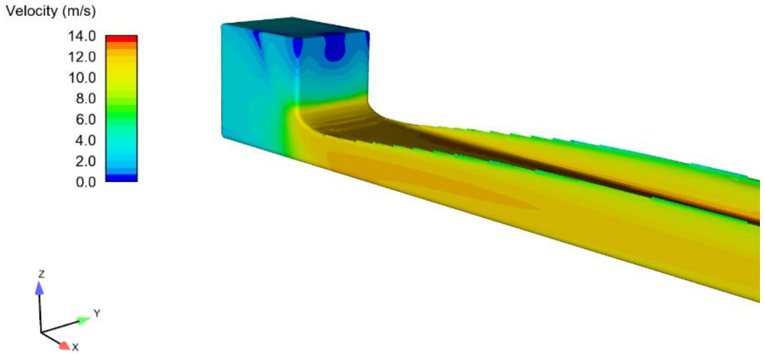
Feb 2016 – Feb 2019

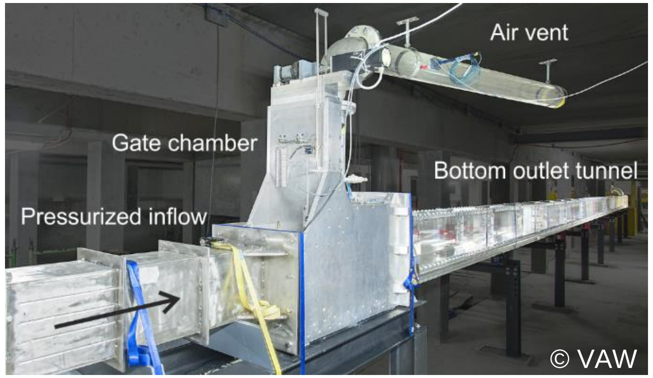
Goal: Develop design guidelines for bottom outlets

- Air demand
- Two-phase flow pattern
- Hydraulics of two-phase flow

Methods:

- Hydaulic scale model ~1:10
- Prototype measurements
- Numerical model





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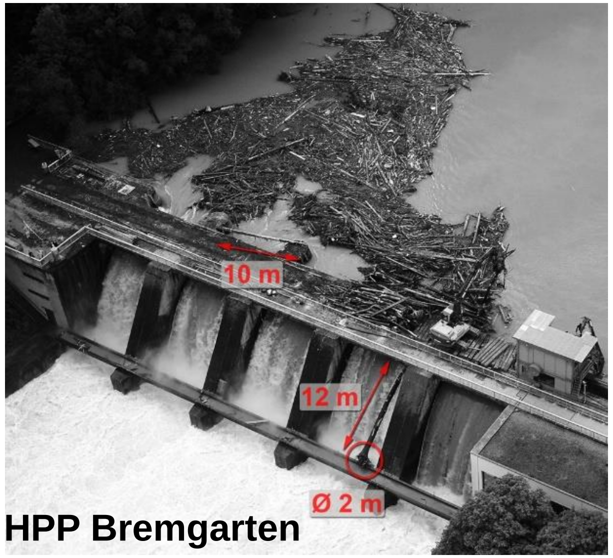
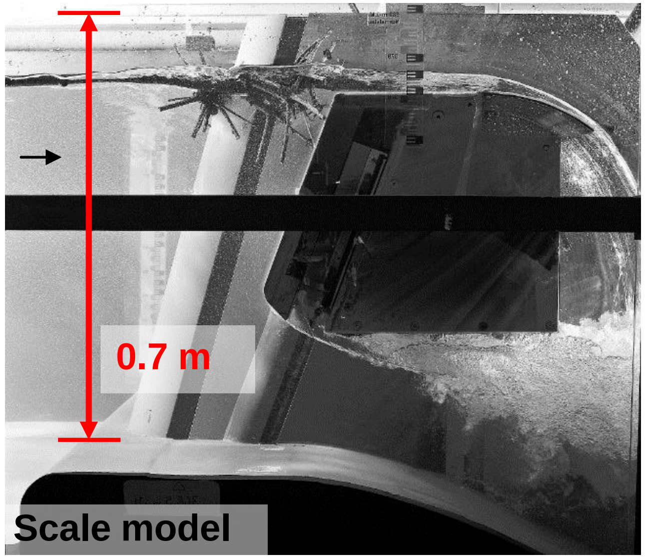
Hydraulic scale models

“Taking the river inside”





Types of similarity

- Geometric similarity
  - Flow depth to tunnel height
  - *Scale* $\lambda = L_{Prototype}/L_{Model}$
- Kinematic similarity / ratio of time scales
  - Velocities in *x* and *y* direction
- Dynamic similarity / ratio of forces
  - Pressure to gravitational forces
  - Geometric & dynamic similarity → kinematic similarity

Hydraulic scale models

Scale laws

Dimensionless Number	Force ratio	Definition
Froude F	Inertia/gravity	$U/(gL)^{0.5}$
Reynolds R	Inertia/viscosity	LU/ν
Weber W	Inertia/surface tension	$(\rho U^2 L/\sigma)$
Euler Eu	Inertia/pressure	$p/\rho U^2$
Cauchy Ca	Inertia/elastic forces	$\rho U^2/E$

E - Bulk modulus of elasitcity $-V\,dp/dV$
L - Characteristic length (e.g. flow depth)
p - Pressure
U - Flow velocity
ν - kinematic viscosity
σ - Surface tension

Ratio between all forces is only equal for λ = 1 (if water is used)

Parameter	unit	scale	factor
Length	[m]	1:λ	10
Time	[s]	$1:\lambda^{0.5}$	3.16
Velocity	[m/s]	$1:\lambda^{0.5}$	3.16
Discharge	[m^3/s]	$1:\lambda^{2.5}$	316
Force	[N]	$1:\lambda^{3}$	1000

Hydraulic scale models

Scale effects

Scale effects are always present – are they negligible?

Spillway chute
Kárahnjúkar Dam (Iceland)

jet trajectory ✓

air entrainment ✗

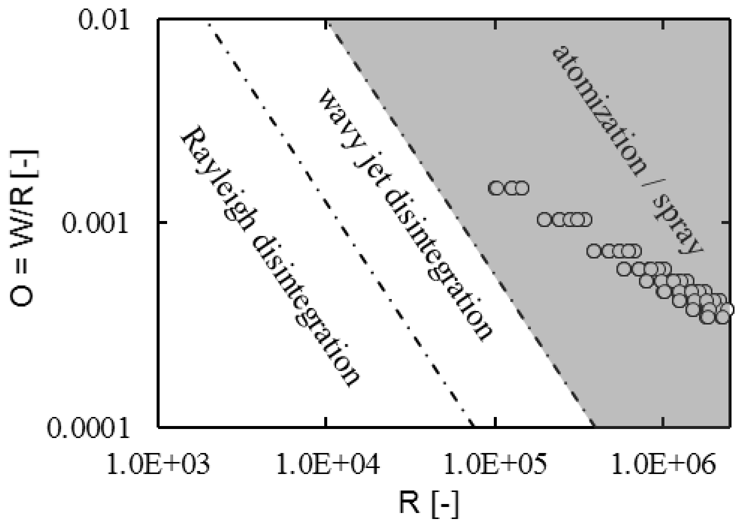
Hydraulic scale models

Assessment of scale effects

Scale effects are always present – are they negligible?

- Scale model family
- Comparison with prototype data
- Literature values
  - e.g. W > 170 (Skripalle 1994)
- Dimensionless numbers need to be sufficiently large
  → same general behavior

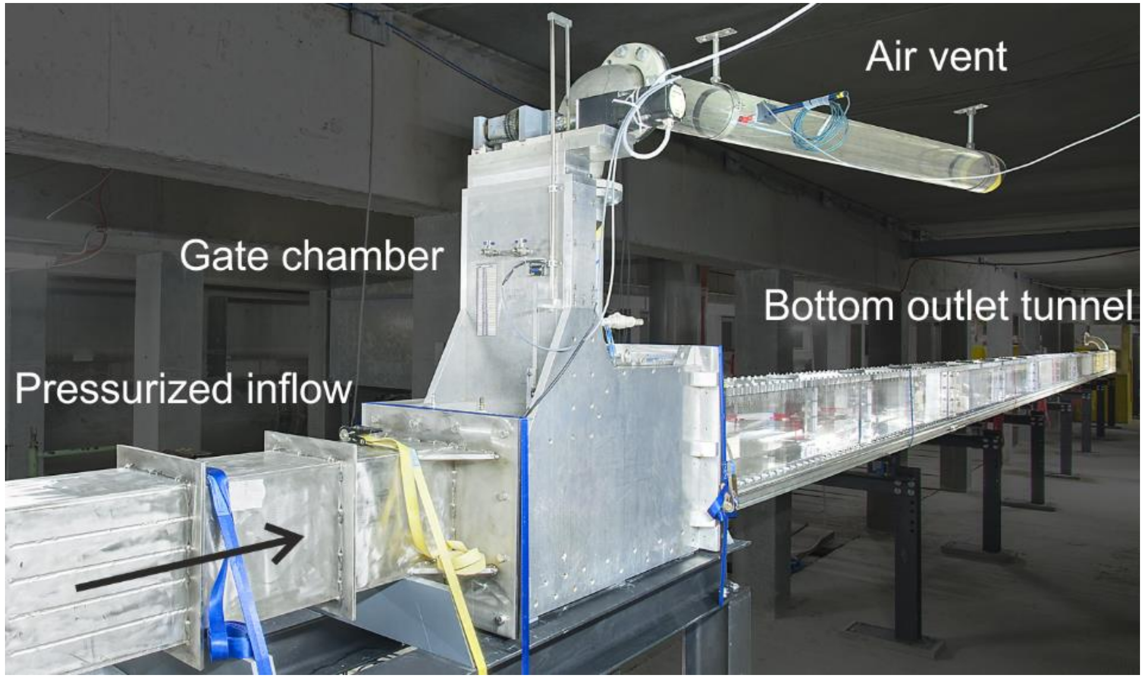
Disintegration of free jets



Ohnesorge (1936)

Model setup

Dimensions

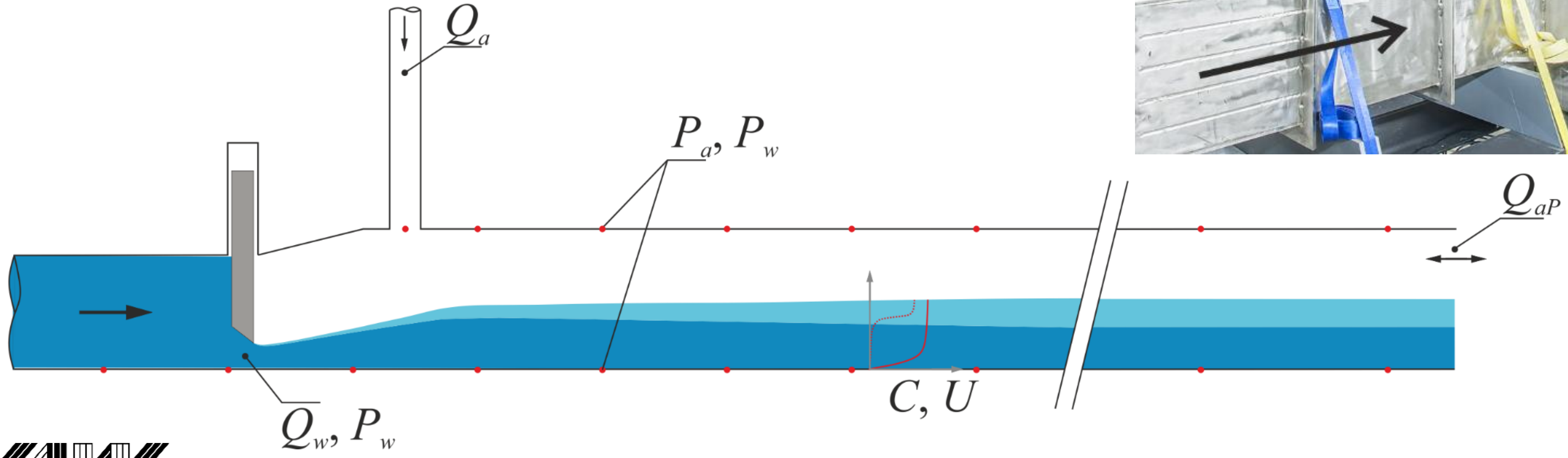


Tunnel geometry

- $L_t * W_t * h_t = 20 * 0.2 * 0.3$ m

Energy head & discharge

- $H_{E,max}$ = 30 m w.c.
- Q_{max} > 600 l/s



Model setup

Instrumentation

Pressure: Piezoresistive pressure sensors

Air velocity: Vane & thermal anemometers

Air concentration & mixture velocity:

- Fiberoptical probe

Keller Druck

Schiltknecht

Model setup
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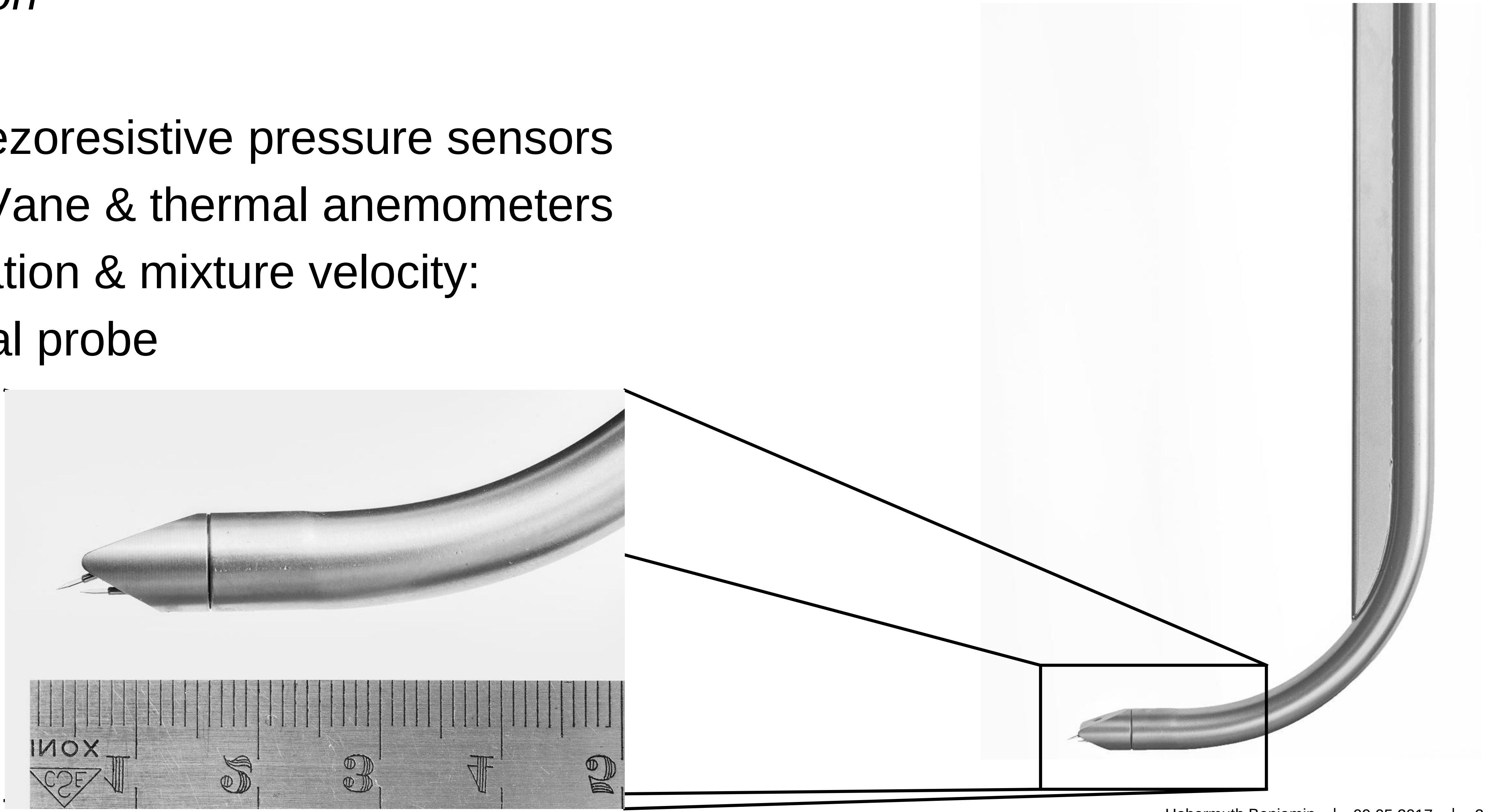

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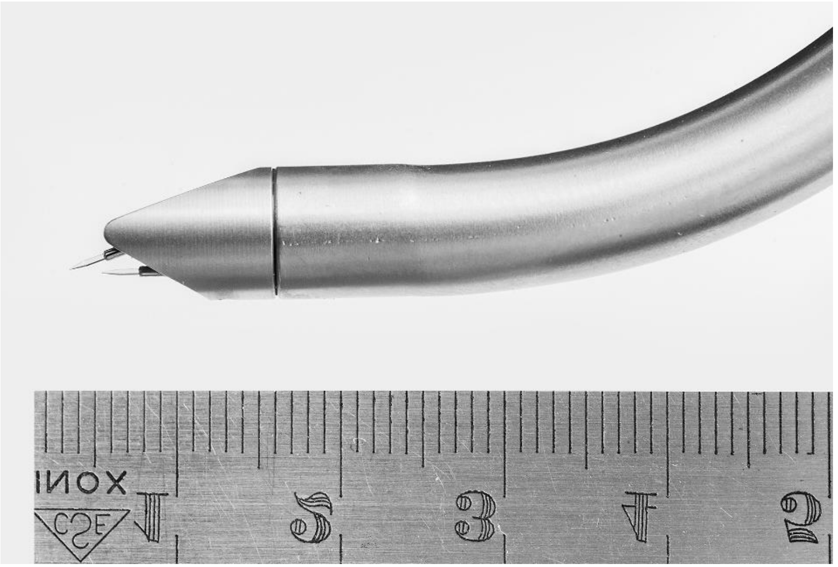
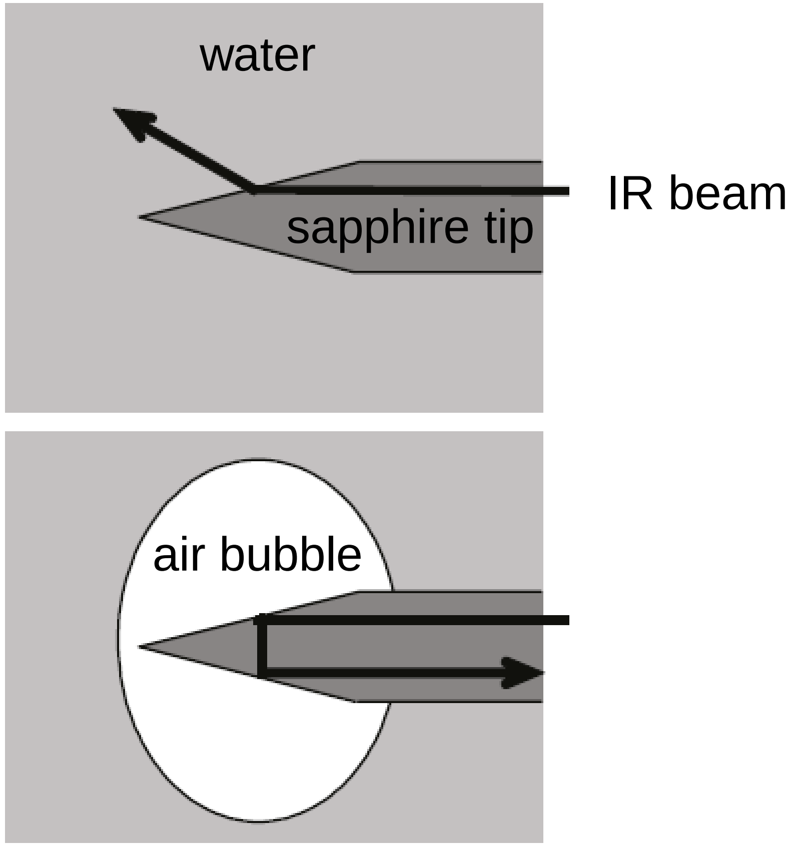
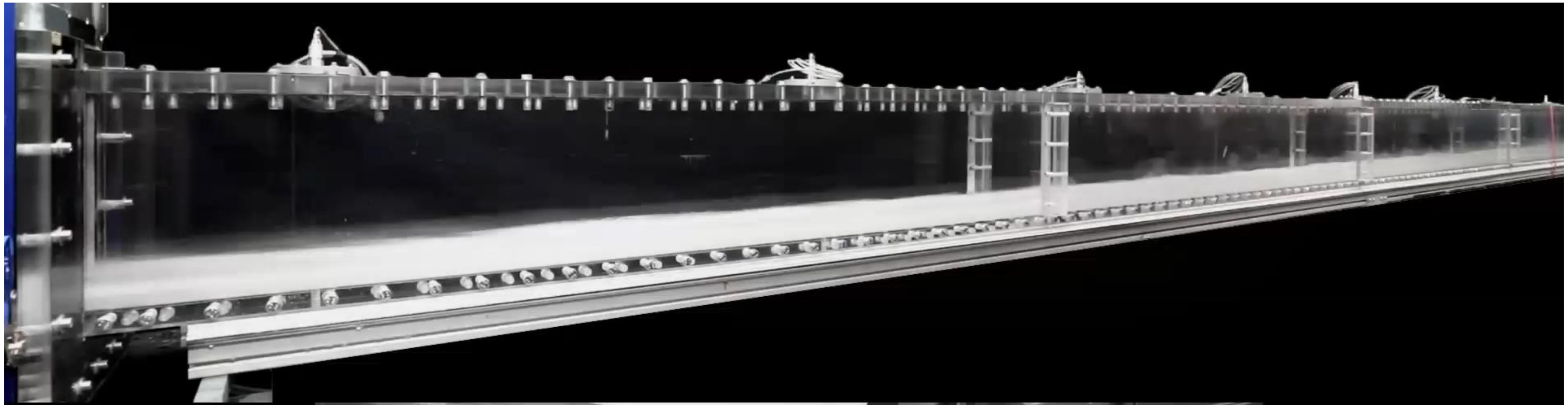




Hydraulic model tests

Movie clip

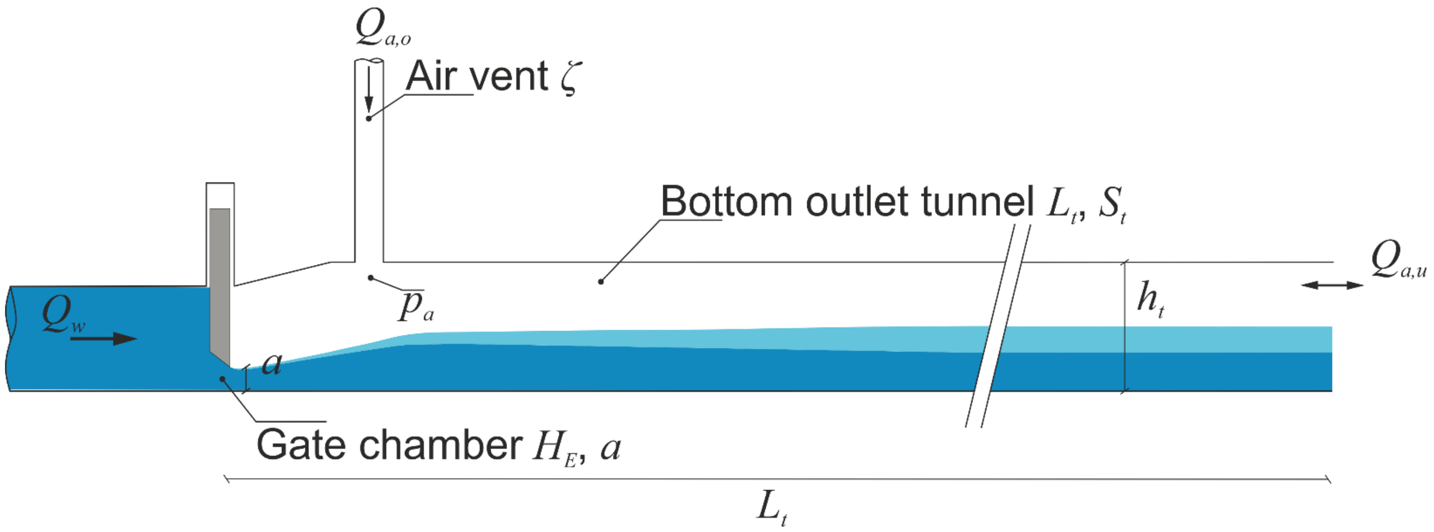


Air demand

Goals

Investigate influence of

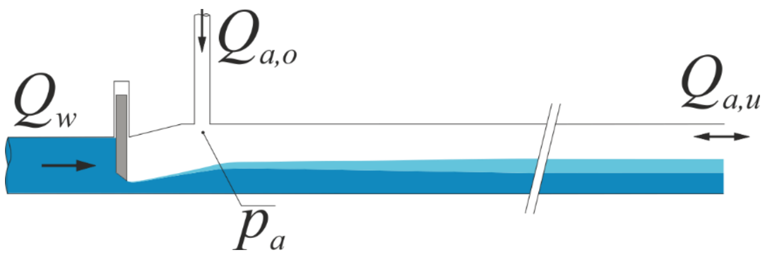
- Energy head H_E
- Gate opening a/a_{max}
- Air vent loss coeff. ζ
- Tunnel length L_t

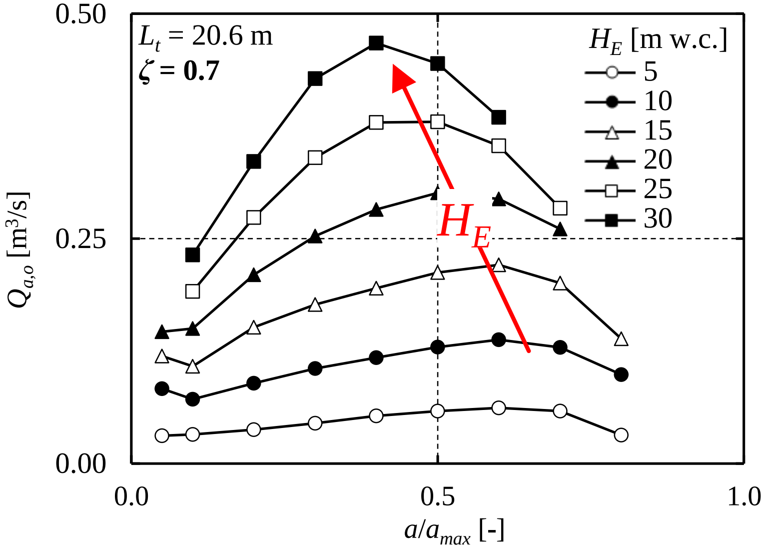


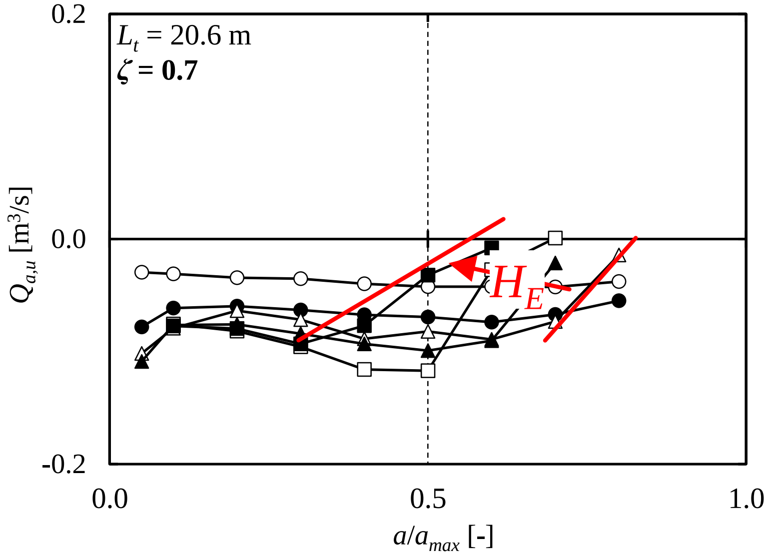
on air demand $\beta = Q_{a,o}/Q_w$ and air pressure p_a

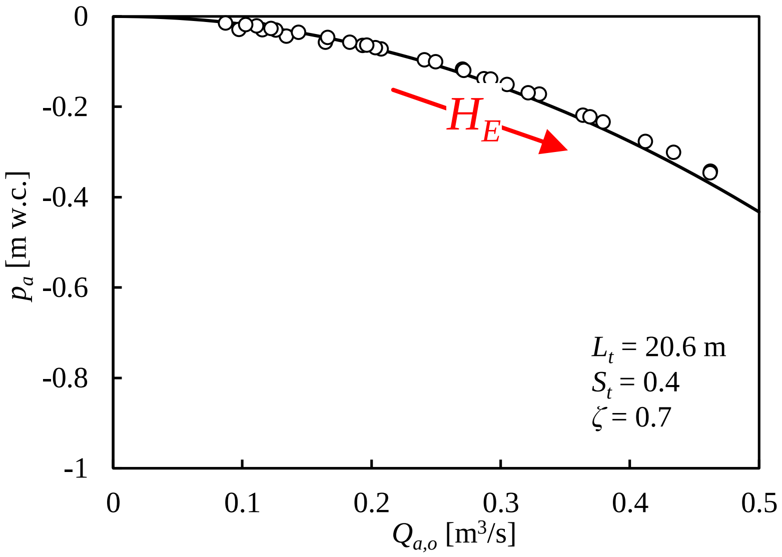
Air demand

Influence of H_E and a/a_{max}



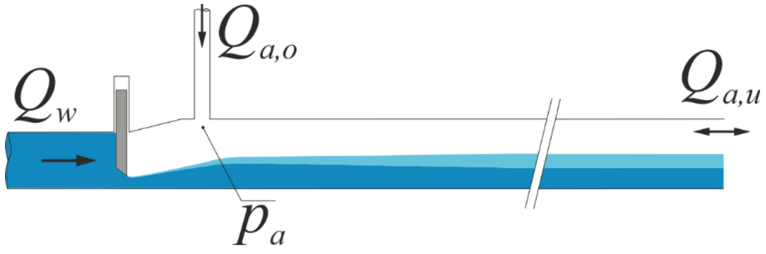


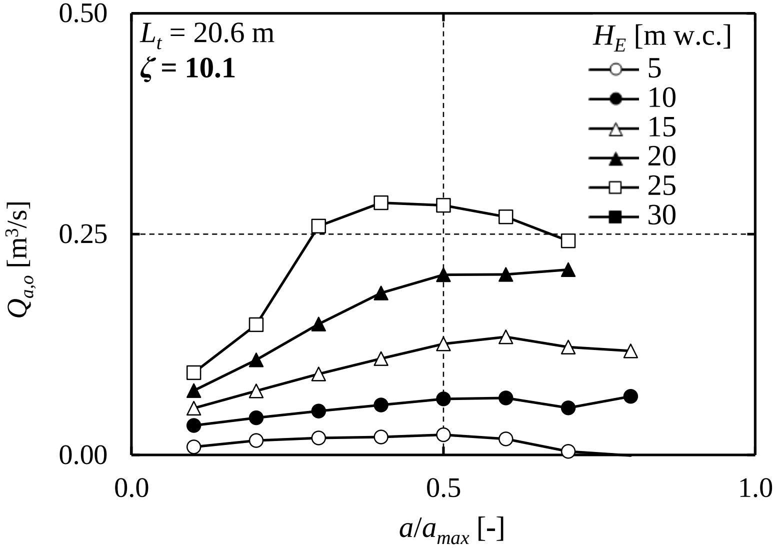


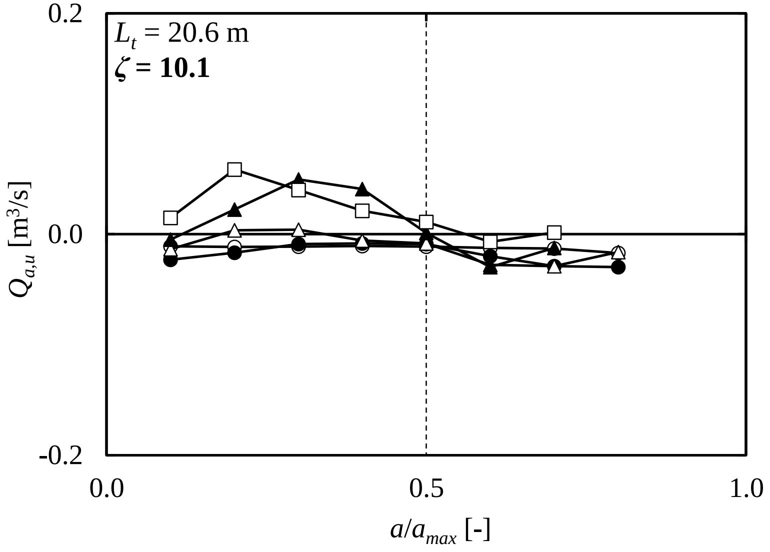


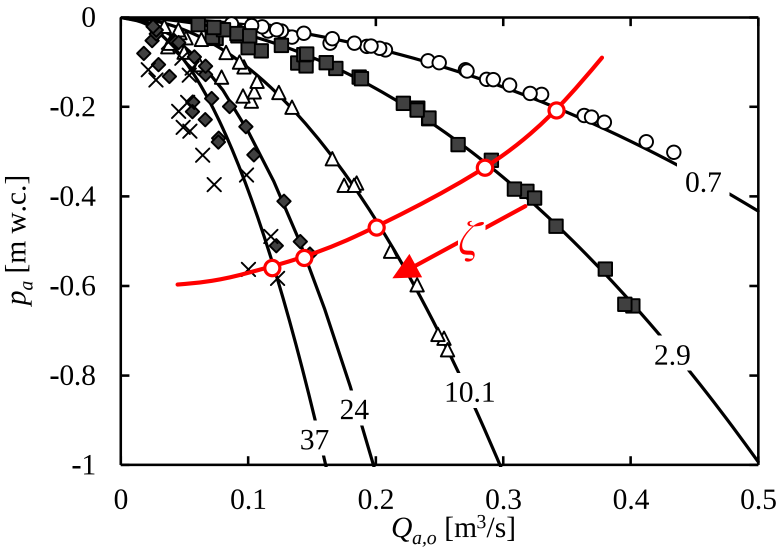
Air demand

Influence of air vent ζ



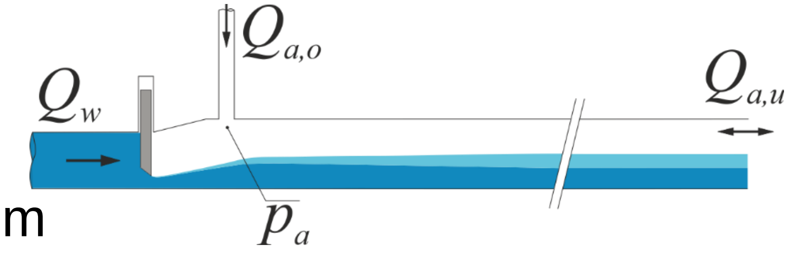


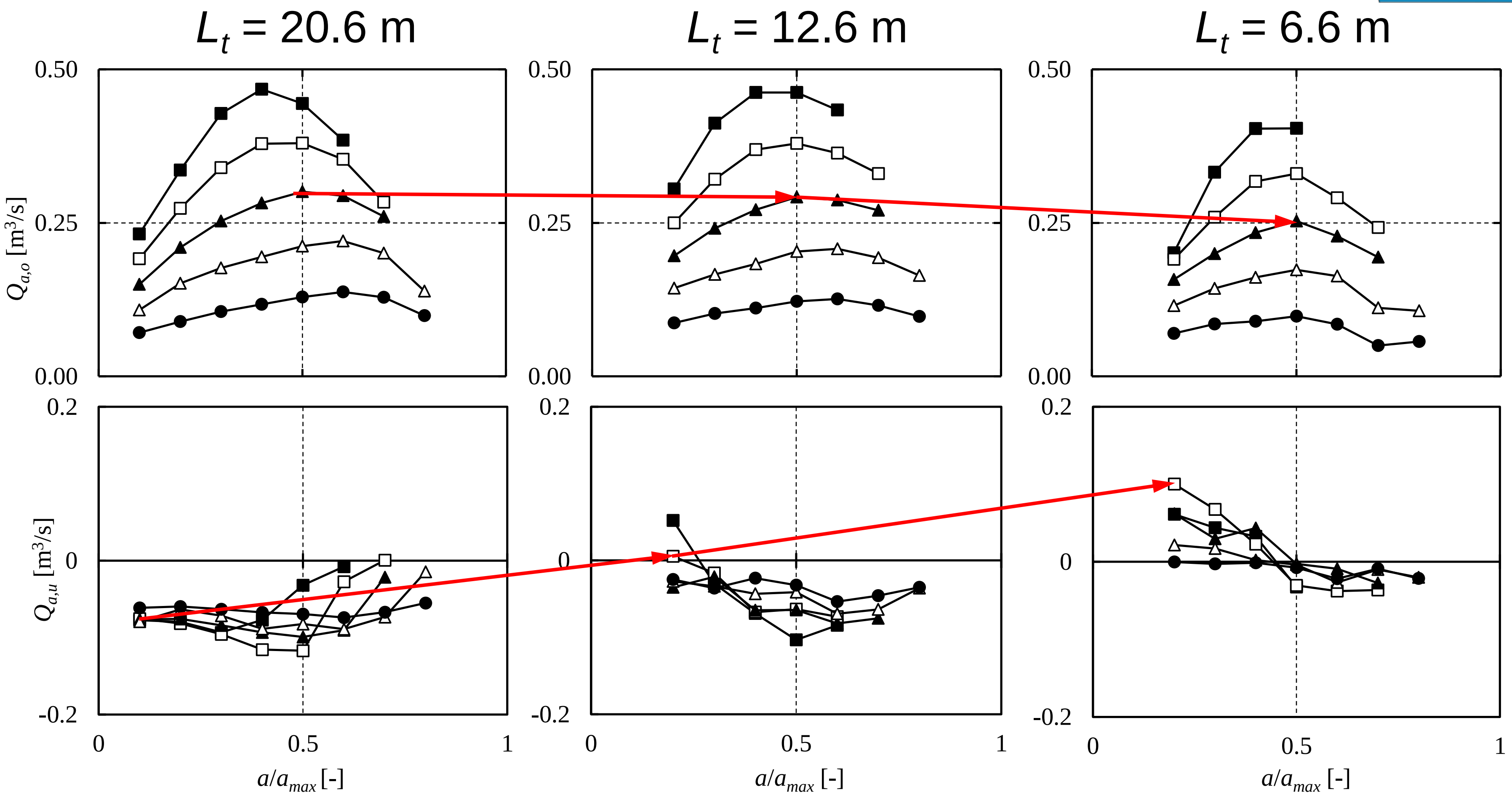




Air demand

Influence of tunnel length L_t



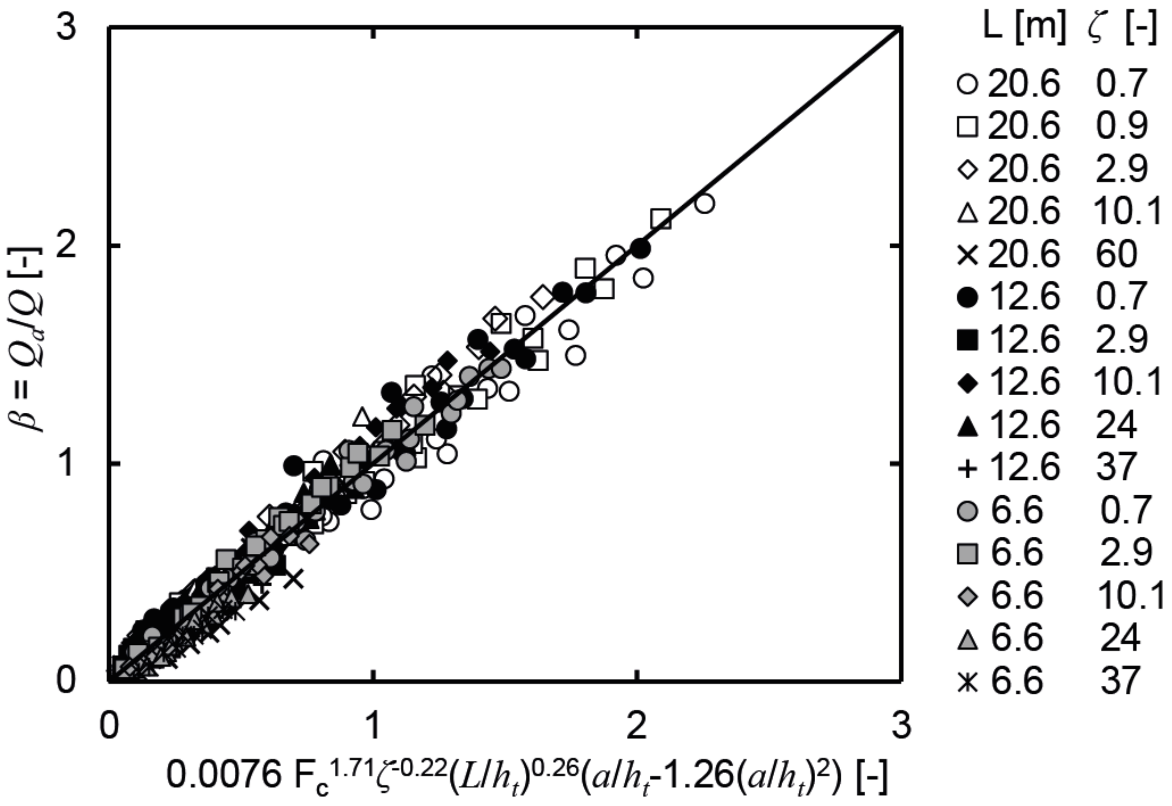


Air demand

Regression analysis

Air demand is a function of:

- Froude number ∝ $F^{1.7}$
- Air vent ζ-value ∝ $\zeta^{-0.22}$
- Relative tunnel length ∝ $L_t/h_t^{\ 0.26}$
- Relative tunnel filling ∝ *quadr. Funct.*



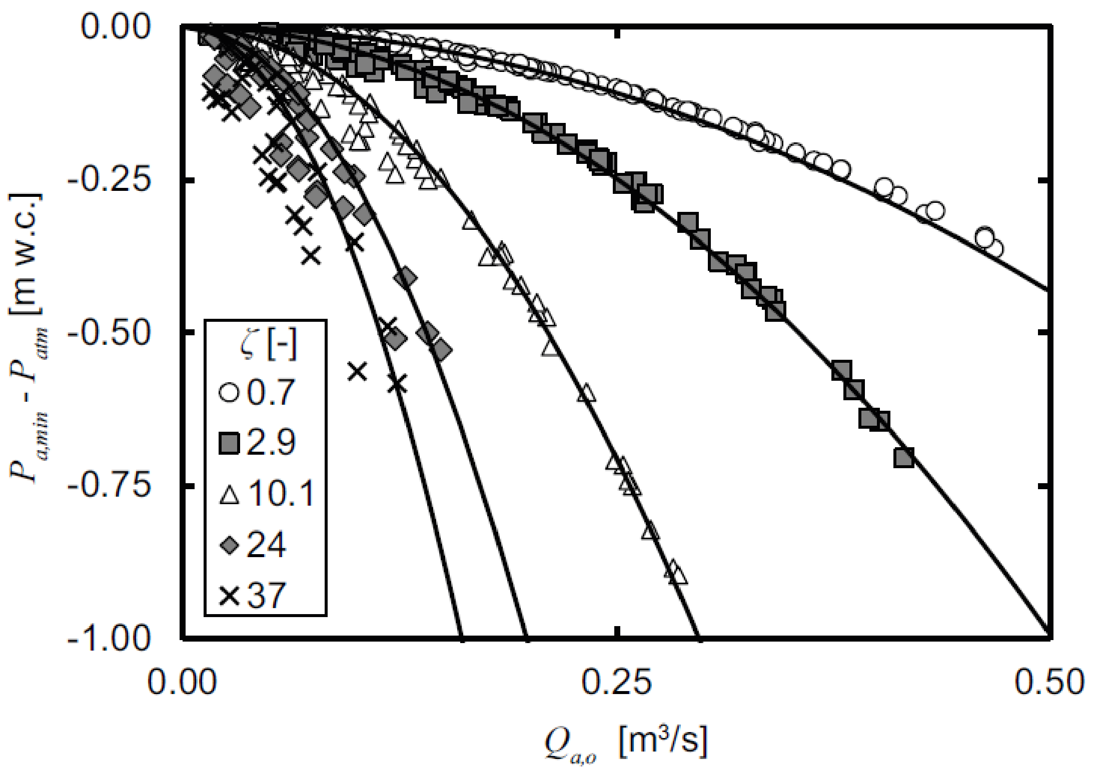
Air demand

Resulting air pressure

Negative air pressure

$$\frac{p_a - p_{atm}}{\rho_a g} = -(1+\zeta)\frac{\left(4Q_{a,o}/\left(d^2\pi\right)\right)^2}{2g}$$

- Only a function of ζ
- Viscosity effects for small $Q_{a,o}$



Prototype measurements

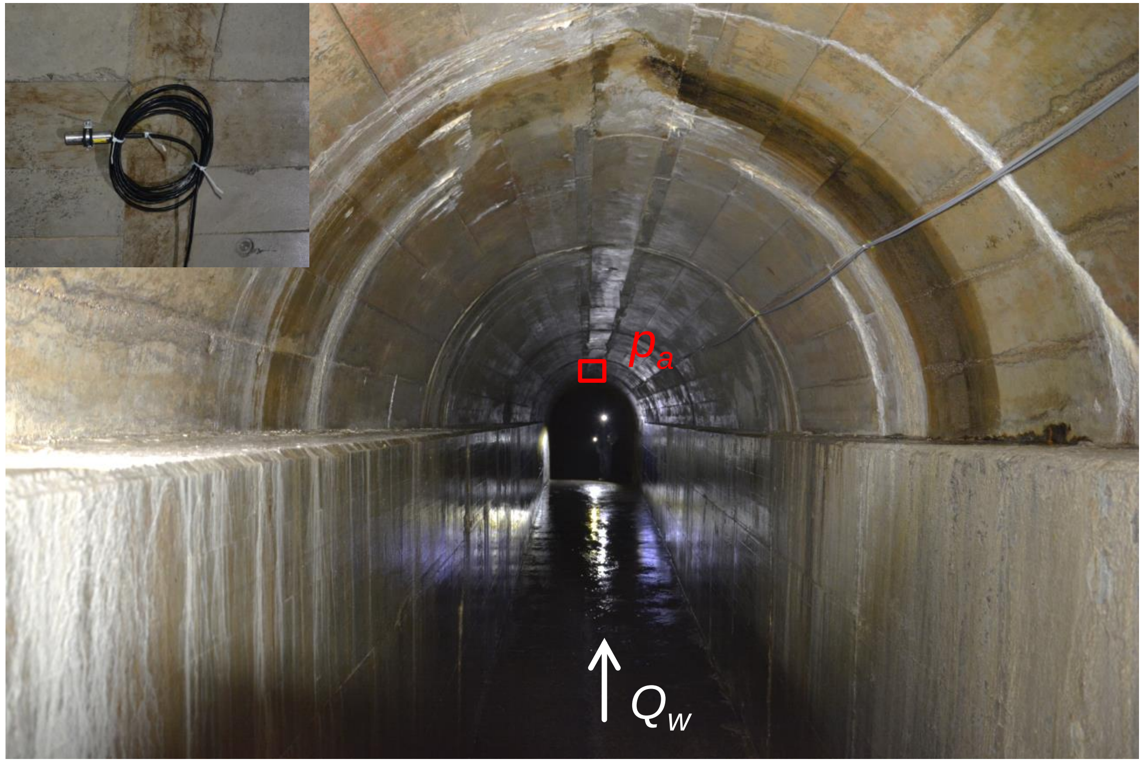
Validation of model test

Malvaglia

- H_E = 90 m w.c.
- L_t = 100 m

Luzzone

- H_E = 220 m w.c.
- L_t = 250 m



Air pressure in outlet tunnel

Air flow through air vent

Prototype measurements

Validation of model test

Malvaglia

- H_E = 90 m w.c.
- L_t = 100 m

Luzzone

- H_E = 220 m w.c.
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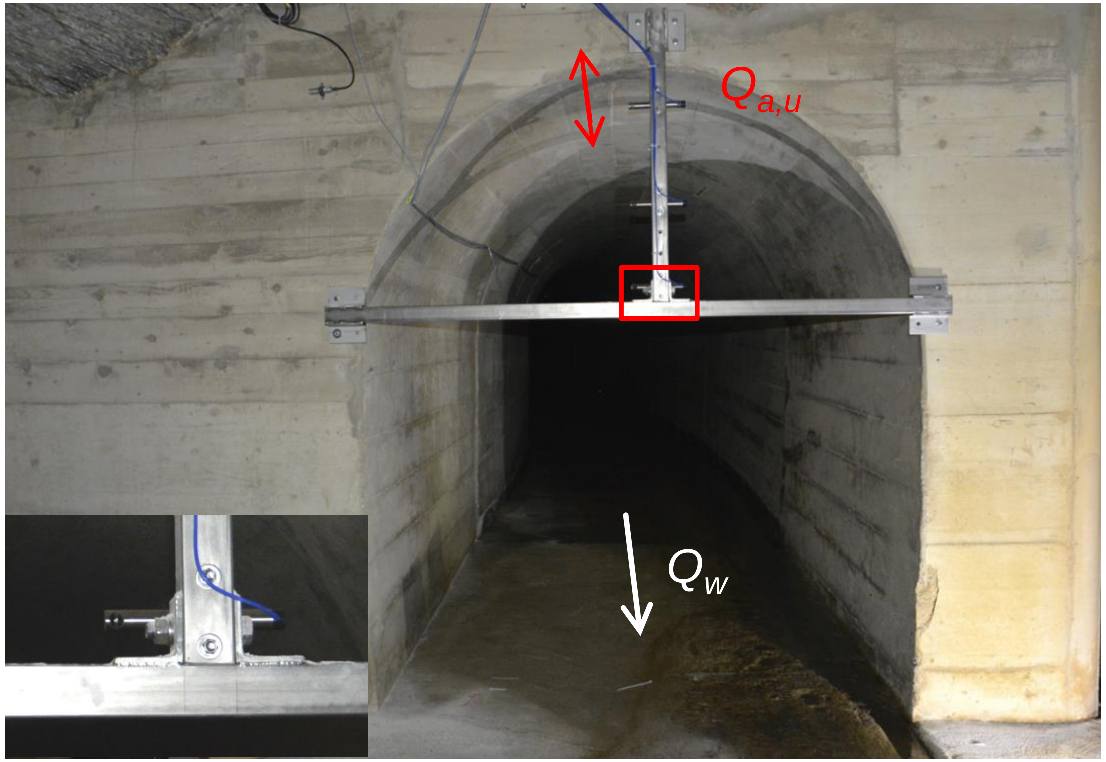


Air flow at tunnel end

Air flow through air vent

Hydraulics of two phase flow

Goals

Investigate

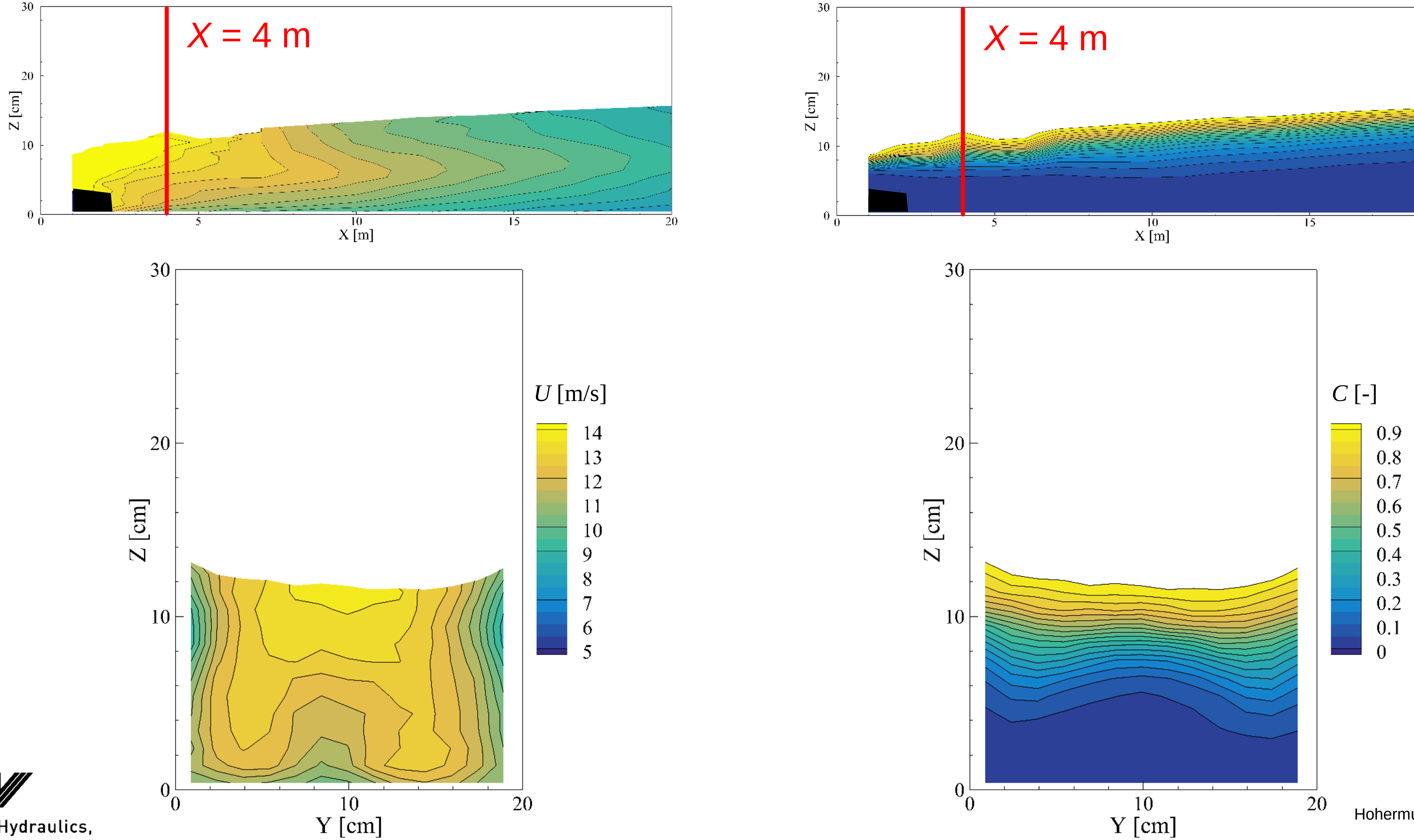
- Development of mean air concentration
- Development of bottom air concentration
- Two-phase flow resistance

As a function of

- Froude number at gate
- Negative air pressure
- Tunnel slope

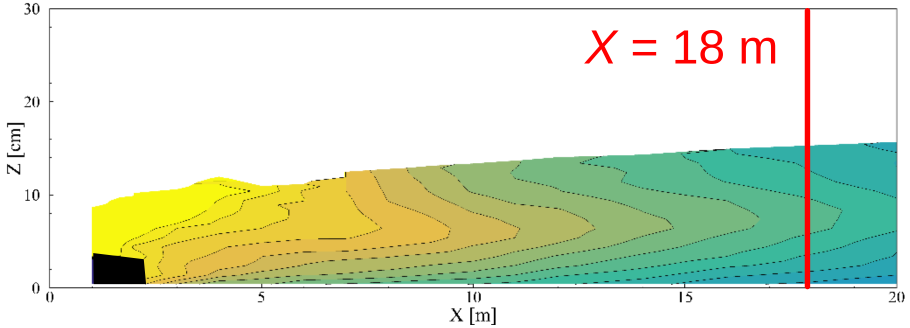
Hydraulics of two phase flow

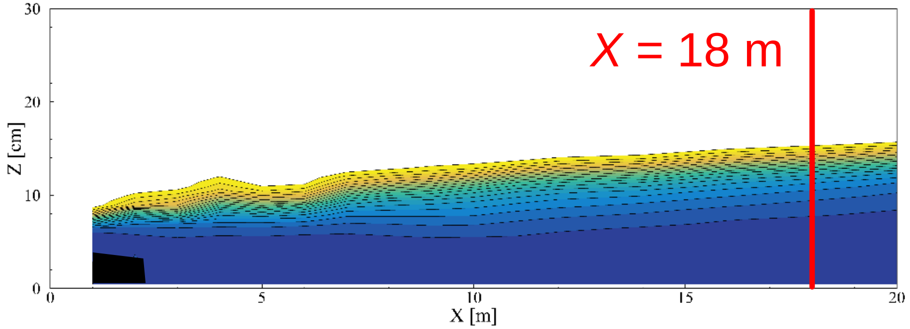
H_E = 10 m w.c., a = 100 mm

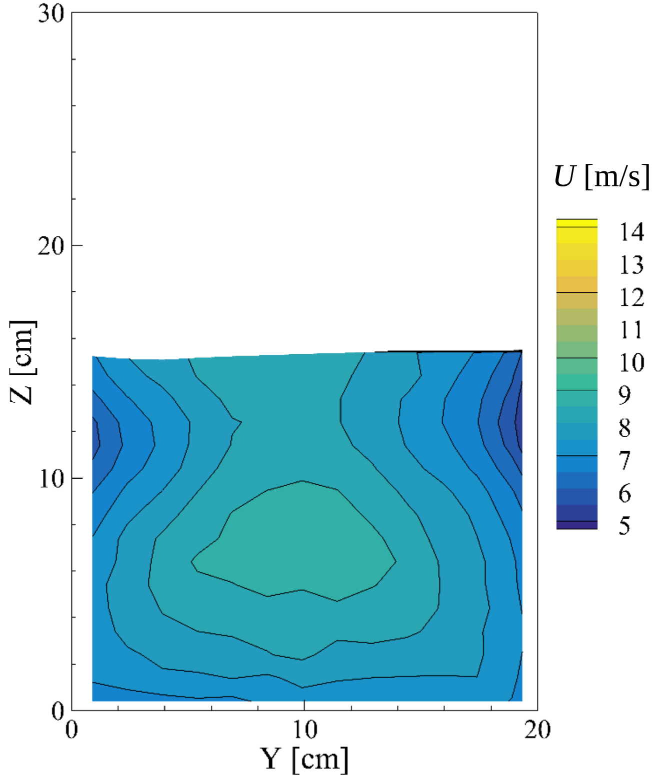


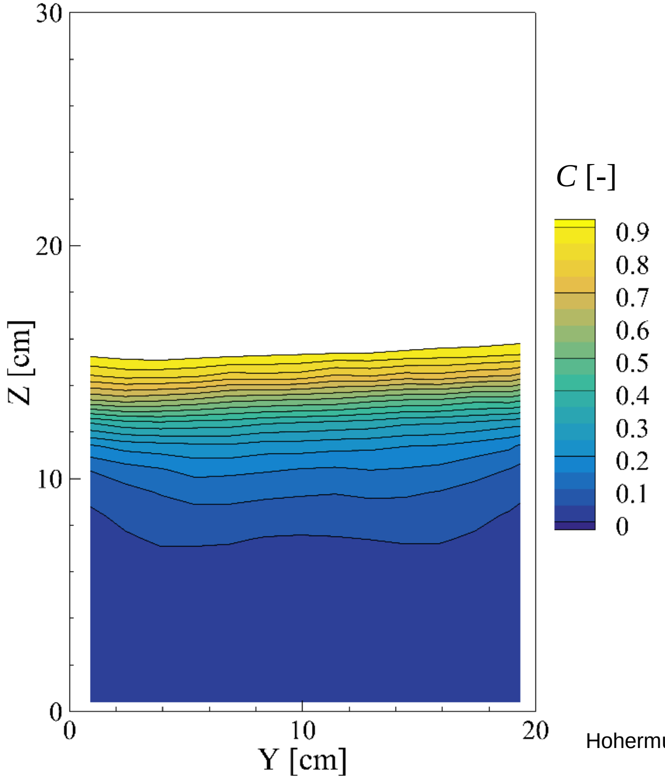
Hydraulics of two phase flow

H_E = 10 m w.c., *a* = 100 mm



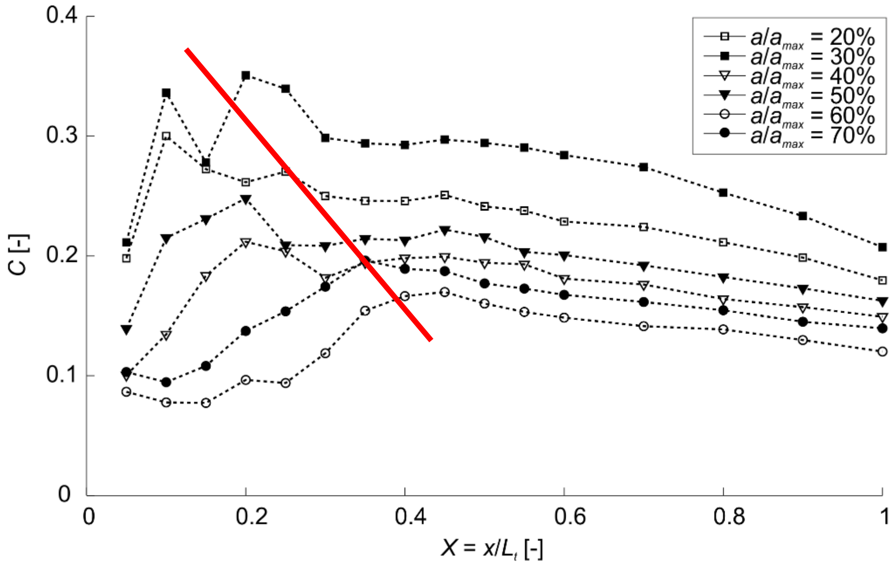


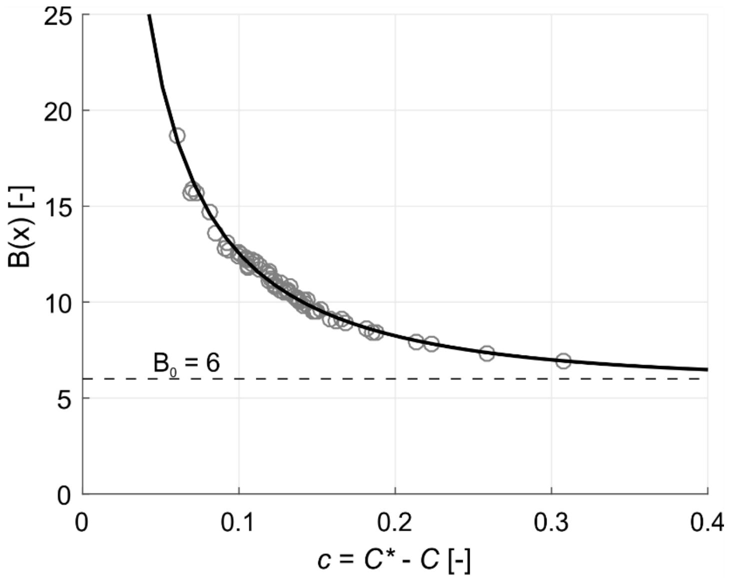




Hydraulics of two phase flow

Mean air concentration – preliminary result



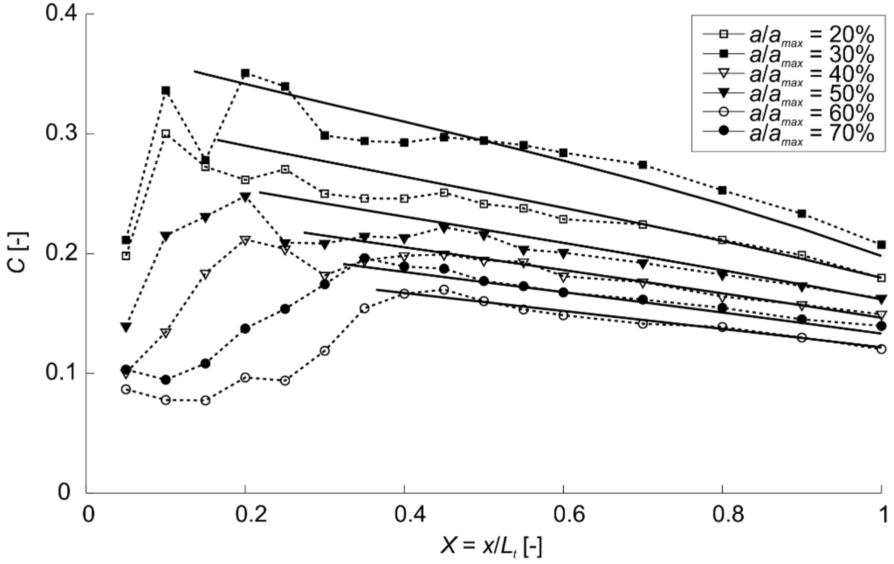


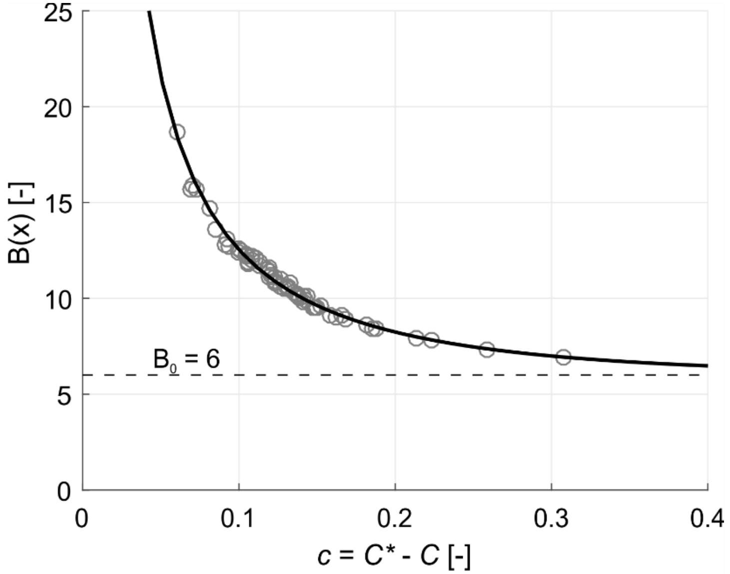
$$\frac{B(x)}{B_0} = \frac{1}{1-e^{-K\cdot c}}$$

$$B = F\sqrt{\frac{2h+w_t}{w_t}} = \frac{U}{\sqrt{g\frac{hw_t}{2h+w_t}}}$$

Hydraulics of two phase flow

Mean air concentration – preliminary result





$$\frac{B(x)}{B_0} = \frac{1}{1-e^{-K\cdot c}}$$

$$B = F\sqrt{\frac{2h+w_t}{w_t}} = \frac{U}{\sqrt{g\frac{hw_t}{2h+w_t}}}$$

Laboratory of Hydraulics, Hydrology and Glaciology

Conclusions

Take home messages

- Swiss Energy Stragety 2050 – storage hydropower
  - Production increase ~3 TWh/a
  - Dam heightening to increase seasonal storage
  - Winter production + 2-3 TWh/a
- Bottom outlets
  - Key safety elements
  - Insuficcient design guidelines
- Experimental results
  - Empirical relation for air demand & air pressure
  - General development of air concentration

Thank you for your attention